UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION III
6TH AND WALNUT STREETS
PHILADELPHIA, PENNSYLVANIA 19106

In reply refer to 3EN33

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RECEIVED
FEB 3 - 1977
WATER POLLUTION BRANCH

Mr. John Egan
Acting Director, Division of
Environmental Control
Department of Natural Resources
Tatnall Building
Dover, Delaware 19901

Re: Llangollen Landfill

Dear Mr. Egan:

Inasmuch as responsibility for issuance of NPDES permits for Delaware has been delegated to the Department, EPA has proceeded slowly and deliberately in its review of the Llangollen Landfill operation. There have been contacts over several months with the Department to ensure that appropriate action would be taken in this matter. Notwithstanding, as part of EPA's overview function of this delegated state program, it has been determined that the Department should immediately require the submission of an application for an NPDES permit by New Castle County for the discharges from its landfill operation.

Available information indicates that water from pumps located at the Llangollen Landfill is conveyed in pipes and discharged into the Army Creek. There is evidence, including Department sampling reports forwarded to EPA, that the water discharged contains pollutants including ammonia nitrogen, chlorides, COD and TOC. Thus, it is concluded that for this operation involving several point sources discharging pollutants into a navigable water an NPDES permit is mandatory.

By reason of the shared concern in this matter, an application for an NPDES permit submitted by New Castle County for the Llangollen Landfill operation is not deemed subject to Waiver Provisions of the Memorandum of Understanding between the Department and EPA.

If you have any questions in this regard, please contact me or Paul Laskow, an attorney on my staff at (215) 597-8915 (Mail Code 3EN33) at the above address.

Sincerely yours,

Stephen R. Wassersug
Director, Enforcement Division

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JAN 24 1977
WATER RESOURCES SECTION

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University of Delaware
Water Resources Center

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WATER RESOURCES
in the vicinity of a
SOLID WASTE LANDFILL
in the
Midvale-Llangollen Estates Area
New Castle County, Delaware

by
R. W. Sundstrom

AR100220

Newark, Delaware
October, 1974

UNIVERSITY OF DELAWARE

Water Resources Center

WATER RESOURCES IN THE VICINITY OF A SOLID-WASTE LANDFILL IN THE MIDVALE-LLANGOLLEN ESTATES AREA, NEW CASTLE COUNTY, DELAWARE

by

R. W. Sundstrom

Newark, Delaware

October 1974

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UNIVERSITY OF DELAWARE

Water Resources Center

WATER RESOURCES IN THE VICINITY OF A SOLID-WASTE LANDFILL IN THE MIDVALE-LLANGOLLEN ESTATES AREA, NEW CASTLE COUNTY, DELAWARE

by

R. W. Sundstrom

Prepared under the sponsorship of

NEW CASTLE COUNTY, DELAWARE, DEPARTMENT OF PUBLIC WORKS

Newark, Delaware

October 1974

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Delaware Geological Survey
Robert R. Jordan, State Geologist

University of Delaware, Department of Geography
John R. Mather, Chairman

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ILLUSTRATIONS

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TABLES

ABSTRACT

The Midvale-Llangollen Estates area comprises about two square miles bordering the Delaware River on the west bank between Army Creek which is located about one and one half miles southwest of New Castle and extending about one and one half miles downstream. The area extends northwestward to include Midvale and Llangollen Estates. The area is underlain by two artesian ground-water aquifers in the Potomac Formation, and one water-table aquifer in the Pleistocene and subcrop of the Upper Potomac aquifer. It is supplied with a small amount of surface water in the northern part of the area from Army Creek.

In 1960 a sanitary landfill was started in the northern part of the Midvale-Llangollen Estates area and completed in 1968. The landfill utilized a worked out gravel pit in which the water table was several feet above the bottom of the pit in several places. The landfill covers an area of about 60 acres and reaches a depth of about 30 feet in many places. In April 1972 leachate contamination from the landfill was discovered southeast of the landfill in the ground water of the Upper Potomac aquifer and in Army Creek. Since the discovery of the leachate contamination, the Department of Public Works in New Castle County has been intensely engaged along with several State agencies to solve and remedy the contamination problem.

This report describes the water resources of the area, describes the geology and hydrologic properties of the ground-water aquifers and appraises the availability of water from the aquifers and Army Creek. The report appraises the available water from each aquifer and relates the hydrology and to other

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properties concerning the aquifer to the ultimate yield of the aquifer, and if appropriate, to the contamination problem so far as available data justify.

The report concludes: (1) the Lower Potomac aquifer is completely developed or nearly completely developed by existing wells in the area; (2) there appears to be little or no danger of leachate contamination from the Llangollen landfill to the Lower Potomac aquifer in the Midvale-Llangollen Estates area; (3) salt-water contamination from the Delaware River has not occurred in the Lower Potomac aquifer in the Midvale-Llangollen Estates area; (4) the limit of development of water from wells in the Upper Potomac aquifer on a sustained basis is estimated to be about 6,500,000 gallons a day or less in the Midvale-Llangollen Estates area; (5) as of January 1, 1974, the Upper Potomac aquifer had received leachate contamination in much of a 310-acre area in the Midvale-Llangollen Estates area; (6) the Pleistocene and subcropping Potomac aquifer beneath and south of the landfill has received leachate contamination and is passing the contamination to the Upper Potomac aquifer in places; (7) Army Creek has received leachate contamination by discharge from the Pleistocene aquifer to the creek in places; and (8) a small rise in chlorides in the water from Amoco Polymer Plant well field wells PW-2 and PW-3 located in the northeastern part of the area is caused by slight leachate contamination rather than salt water from the Delaware River.

The report recommends that the operation of the retrieval wells be continued until the leachate contaminants are removed from the Upper Potomac and Pleistocene aquifers in the vicinity of the Llangollen landfill. The report also recommends that the Llangollen landfill be removed, or that the leachate be completely contained within the landfill, or that the leachate discharge from the landfill be completely captured by protective pumpi g at and near the landfill.

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INTRODUCTION

Purpose and Scope of the Report

This report gives the results of a study of the water resources in the Midvale-Llangollen Estates area, New Castle County, Delaware, and relates the hydrologic effect of a solid-waste landfill in the area on these resources. The Midvale-Llangollen area covers about two square miles. It includes Midvale in the northwest corner; Llangollen Estates in the southwest corner; the mouth of Gambles Gut in the southeast corner; and the mouth of Army Creek in the northeast corner of the area.

The study and this report have been made under a contractual agreement between the New Castle County Department of Public Works and the University of Delaware Water Resources Center. Primary objectives of the study include: (1) the gathering, study and evaluation of hydrologic data relating to the ground-water aquifers in the area and Army Creek; (2) evaluating the hydrologic relationship of the leachate discharge from a solid-waste landfill to the waters in the ground-water reservoirs and Army Creek; and (3) making such recommendations and comments as the study justifies. The scope of the study includes: (1) collection and analysis of data pertaining to the occurrence and hydrology of the ground and surface waters in the Llangollen area; (2) collection and study of available quality of water; (3) study and review of all hydrologic properties of the ground and surface water supplies in the area; (4) illustrate movement of ground water in the landfill area; (5) study transmissive properties of the aquifer; (6) study recharge relation to flow and

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surface water discharge; (7) relate the hydrologic properties of the landfill, the ground-water aquifers, and the flow of Army Creek to each other; (8) study the extent of contamination of the ground-water aquifer; (9) summarize the results of this study; and (10) prepare a report on the results of this study.

A large amount of geological and hydrological data that apply to the Midvale-Llangollen Estates area has been gathered. Three reports written by Sundstrom and others (1967, 1971, 1971) include the Midvale-Llangollen area. After landfill leachate was discovered in the ground water in the area in 1972, a very large amount of test drilling, data gathering, study and remedial work has been undertaken by the New Castle County Department of Public Works and their consultant, Roy F. Weston, Incorporated. Likewise, the Division of Environmental Control of the Delaware Department of Natural Resources and Environmental Control and the Delaware Geological Survey have been active in the study. The Water Resources Center became active in the study late in 1973 through the agreement with New Castle County mentioned above.

During the course of this study, data furnished by the above-mentioned agencies have been used freely. Also aerial photographs were used from the Department of Geography, University of Delaware. Consulting reports by Leggette, Brashears and Graham and Geraghty and Miller on the Avisun plant and Geraghty and Miller on the Artesian Water Company Llangollen well field have been used. Data collected by Sundstrom (1967, 1971 and 1971) and data from the files of the Water Resources Center have been used. Other data have been furnished by many individuals.

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Personnel and Acknowledgments

Dr. Robert D. Varrin, Director, Water Resources Center, University of Delaware, has had the responsibility of coordinating, planning and directing the study. The study was made and the report prepared by Mr. R. W. Sundstrom, Senior Research Hydrologist at the Water Resources Center. Dr. Varrin and his staff have given complete support to this study and the preparation of this report. The author is particularly grateful to Dr. Varrin for his good counsel and to Mrs. Beverly Grunkemeyer and Mrs. Donna Henderson for their excellent assistance in preparing this report. Likewise the author is grateful to Mr. Albert W. Madora, Director of the Department of Public Works, New Castle County, and his staff for making their data available for the study. He especially extends thanks to Mr. Madora, Mr. Warren O'Sullivan, Mr. Stephen Kowalchuk, Mr. David Clark and to consultants to New Castle County, Mr. Roy F. Weston, Inc. Mr. N. C. Vasuki of the Division of Environmental Control and his staff members, Mr. Lee Beetschen and Mr. Frank Moorshead, furnished useful data used in this report. Dr. Robert R. Jordan, State Geologist, and his staff have furnished many reports and data from the files of the Delaware Geological Survey. Dr. J. R. Mather, Chairman, Department of Geography of the University of Delaware, and his staff provided aerial photographs. Many others furnished data or information used in this study and report for which the writer is grateful. Appreciation is extended to Mr. Kenneth Woodruff and others of the Delaware Geological Survey, Mr. Richard Johnston of the U. S. Geological Survey, Mr. Albert Madora and Mr. Warren O'Sullivan of the New Castle County Department of Public Works, and Dr. Robert D. Varrin of the Water Resources Center for their review of the report draft.

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Previous Investigations

Several reports prepared in the last three decades when used in conjunction with data obtained in the present study of the water resources in the Midvale-Llangollen Estates area give important hydrologic data. Notable among the prior reports are the following:

(1) Water level measurements published by the U. S. Geological and the Delaware Geological Surveys

(2) Hydrologic Atlas 79 by the U. S. Geological Survey giving the ranges in the water table for the period 1950-1961

(3) Delaware Geological Survey, Bulletin 4, 1955, by I. W. Marine and W. C. Rasmussen, giving data on ground-water development prior to 1953

(4) Ground-Water Resources of the Tri-State Region Adjacent to the Lower Delaware River, New Jersey Department of Conservation, Division of Water Policy and Supply, Special Report 13, 1958, by H. C. Barksdale and others

(5) Hydrochemical Facies and Ground-Water Flow Patterns in the Northern Part of the Atlantic Coastal Plain, U. S. Geological Survey Professional Paper 498-A, 1966, by William Back

(6) The Water Resources of Northern Delaware, Delaware Geological Survey, Bulletin 6, 1956, by W. C. Rasmussen and others

(7) The Availability of Ground Water in the Potomac Formation, Water Resources Center, University of Delaware, 1967, by R. W. Sundstrom and others

(8) Water Supply and Use in the Drainage Basins of the Delaware River System and Atlantic Coastal Drainage Basins in Delaware, Water Resources Center University of Delaware, 1971, by R. W. Sundstrom and R. D. Varrin

(9) The Availability of Ground Water in New Castle County, Delaware, Water Resources Center, University of Delaware, 1971, by R. W. Sundstrom and T. E. Pickett

(10) Potential Ground-Water Supply at Tidewater Associated Oil Company Refinery Site, Delaware City, Delaware, 1955. Consulting report by Leggette and Brashears

(11) Ground-Water Conditions in the Vicinity of the Avisun Plant near New Castle, Delaware, 1961. Consulting report by Leggette, Brashears and Graham

(12) Summary of Ground-Water Exploration along the Chesapeake and Delaware Canal in Delaware and Maryland, 1967. Consulting report by Geraghty and Miller

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(13) Report of Ground-Water Investigation Avisun Plant, New Castle, Delaware, 1966, A. C. Schultes and Son

(14) Construction of a 6-inch Diameter Test Well for Avisun Corporation, 1966, A. C. Schultes and Son

(15) Occurrence of Chlorides in the Shallow Artesian Aquifer, Avisun Corporation, New Castle, Delaware, 1970. Consulting report by Geraghty and Miller

(16) Evaluation of the Ground-Water Conditions in the Llangollen Well Field, Artesian Water Company, Newport, Delaware, 1973. Consulting report by Geraghty and Miller

(17) Preliminary Investigation of Ground-Water Contamination Associated with the Llangollen Landfill, New Castle County, Delaware, 1972. Consulting report to New Castle County, Delaware, by Roy F. Weston, Inc.

(18) Preliminary Feasibility Study, Leachate Control Strategies for Llangollen Landfill, New Castle County, Delaware. Consulting report to New Castle County, Delaware, 1974, by Roy F. Weston, Inc.

(19) Water Resources of the Delmarva Peninsula by E. M. Cushing, I. H. Kantrowitz and K. R. Taylor, 1973, U. S. Geological Survey Professional Paper 822

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GEOLOGY

The geology described herein is abstracted from the report by Sundstrom and Pickett, 1971, entitled, "The Availability of Ground Water in New Castle County, Delaware." Only the geology pertaining to the rocks that underly the Midvale-Llangollen Estates area has been abstracted from the report. For a more complete discussion of the geology of the formations underlying New Castle County, the reader is referred to the earlier report.

General Geology of New Castle County

New Castle County encompasses portions of two regional geologic provinces: the Appalachian Piedmont and the Atlantic Coastal Plain (Figure 1, Tables 1 and 2). The northernmost part of the county, characterized by gently rolling hills, lies in the Piedmont Province. The surface of this complex of very old metamorphic and igneous rocks slopes seaward, forming the basement upon which lies the wedge-shaped mass of sedimentary rock of the Coastal Plain. This wedge consists largely of unconsolidated clays, silts, sands, and gravels which reach a thickness of more than 2,300 feet in southeastern New Castle County. It is part of the Atlantic Continental Shelf and represents a landward extension of an enormous trough of sedimentary rocks parallel to the coastline. This trough constitutes [illegible] Atlantic Coast Geosyncline.

Most of the Piedmont in Delaware is underlain by the Wissahickon Schist. The older Cockeysville Marble is exposed in two small areas at the crests of unroofed anticlines. These two units of metamorphosed sedimentary rock belong

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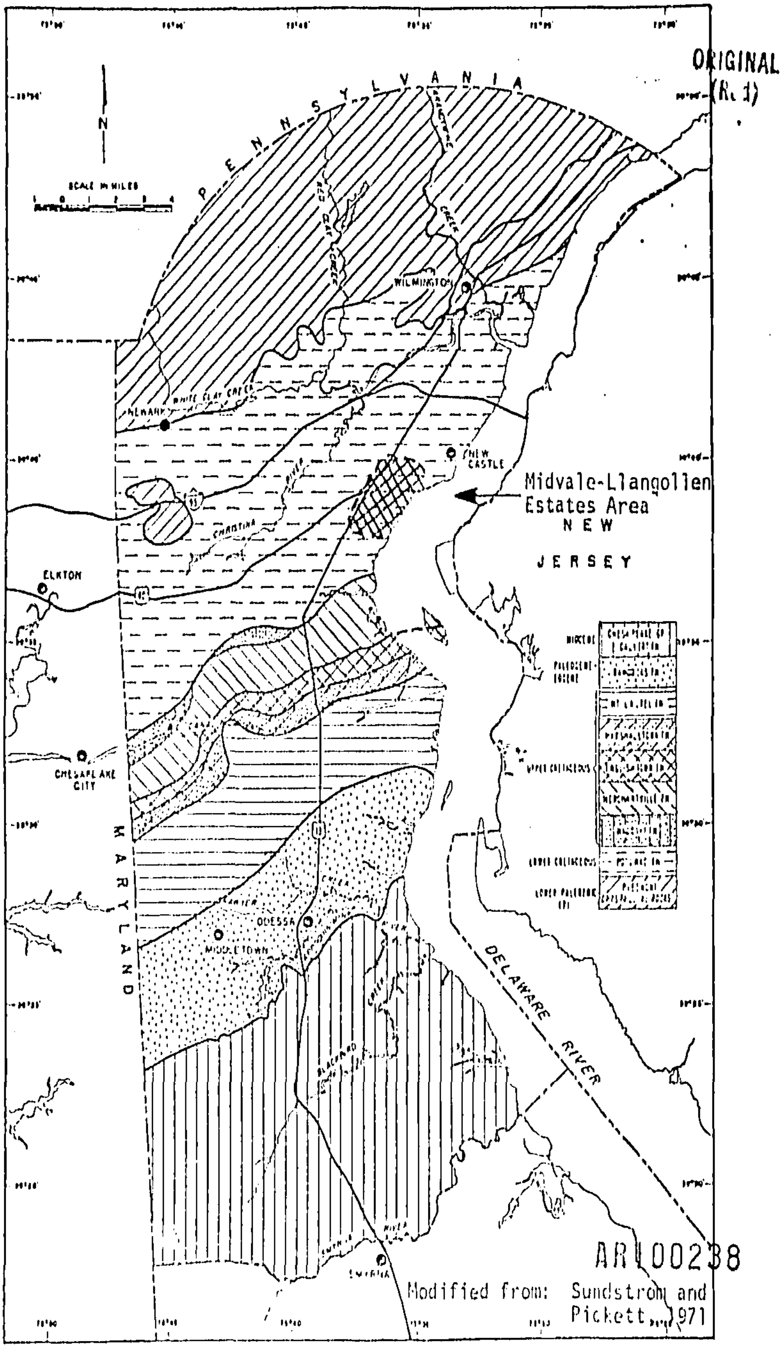

FIGURE 1 GEOLOGIC MAP OF NEW CASTLE COUNTY (PLEISTOCENE REMOVED).

		New Jersey	Delaware		Maryland
Quaternary	Pleistocene	Cape May Fm.* Pensauken Fm.* Bridgeton Fm.*	Columbia Fm (Aquifer)	Omar Fm. Beaverdam Fm (Columbia Gr.)	Parsonsburg Sand† Pamlico Fm.† Talbot Fm.† Walston Silt† Beaverdam Sand
Tertiary	Pliocene (?)	Beacon Hill Gravel*	Bryn Mawr Fm.	Brandywine Fm (?)	Brandywine, Bryn Mawr, and Beacon Hill Gravels (tentative)
	Miocene	Cohansey Sand Kirkwood Fm.	Chesapeake Gr.	Aquifers Pocomoke Manokin Frederica Cheswold	Chesapeake Gr.: Yorktown and Cohansey Fms.†, St Marys Fm., Choptank Fm., Calvert Fm. Aquifers:† Pocomoke, Manokin
	Oligocene				
	Eocene	Piney Point Fm. (?) Shark River Fm. Manasquan Fm.	Unit C (Aquifer)	Piney Point Fm. Unit A	Chickahominy Fm. Piney Point Fm. Pamunkey Gr.: Nanjemoy Fm., Aquia Fm.
	?				
	Paleocene	Rancocas Gr.: Vincentown Fm., Hornerstown Fm.	Rancocas Fm. (Aquifer) Unit B		Brightseat Fm.
Cretaceous	Upper Cretaceous	Monmouth Gr.: Tinton Fm.**, Redbank Fm, Navesink Marl, Mt. Laurel Sand	Monmouth Gr.: Redbank Fm ?, Mt Laurel Fm.	Monmouth Fm.	Monmouth Fm.
		Matawan Gr.: Wenonah Fm., Marshalltown Fm, Englishtown Sand, Woodbury Clay, Merchantville Fm.	Matawan Gr.: Marshalltown Fm, Englishtown Fm., Merchantville Fm	Matawan Fm.	Matawan Fm.
		Magothy Fm.	Magothy Fm.		Magothy Fm.
		Raritan Fm.	Potomac Fm		Potomac Gr.: Raritan Fm.
	Lower Cretaceous	Patuxent and Patapsco Fms.			Potomac Gr.: Patapsco Fm, Arundel Clay, Patuxent Fm.

Table 2. Correlation chart of the Coastal Plain units in New Jersey, Delaware, and Maryland. The section for New Jersey is adopted from Kaschbach and Scudder (1961) and Kummel (1940). The Maryland section is adopted from Rasmussen and Slaughter (1955).

*Not always separable into formations and may be collectively termed "yellow gravel series".

**Monmouth County only.

†Divisions recognized only in part of the Eastern Shore

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to the Glenarm Series which is of great extent in the Appalachian Piedmont. Igneous and meta-igneous rocks adjacent to the Glenarm Series have been named the Wilmington Complex and are described in detail by Ward (1959). The Complex consists largely of coarsely and vaguely banded gneiss with prominent amounts of gabbro, amphibolite, and granite. The Port Deposit Granodiorite, an important unit in nearby Maryland, appears to intrude the Complex at its southwestern margin.

Severe metamorphism has obscured the age relationships of the rocks of the Piedmont. The Glenarm Series was probably deposited in early Paleozoic (or possibly Late Precambrian) time. The Wilmington Complex is thought to be younger and may have been intruded during the metamorphism of the Glenarm rock.

The much younger sand and gravel of the Bryn Mawr Formation forms a cap on the higher hills of the metamorphic rocks north of Wilmington.

Physiographically the border of the Piedmont with the Coastal Plain Province is marked by the Fall Zone. In this zone the gradients of streams entering upon the easily eroded Coastal Plain sediments from the Piedmont increase and rapids are formed on the crystalline basement where the sediment is removed. The crystalline rocks extend far to the east beyond the Fall Zone to make up the basement on which the Coastal Plain sediments have been deposited.

The oldest sediments of the Coastal Plain in New Castle County are of Early Cretaceous age. Deposition of these continental materials continued into the Late Cretaceous. Marine transgression is considered to have occurred in the Turonian. Marine deposition continued thereafter with little or no interruption until the Late Eocene. No Oligocene sediments are known from the northern Atlantic Coastal Plain. Deposition resumed in the latter part of the Miocene and was interrupted again by a period of non-deposition and erosion

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during the Pliocene and perhaps part of the Pleistocene. Columbia fluvial deposits cover almost the entire surface of the New Castle County Coastal Plain. Except for the outcrops of the Cretaceous units in the banks of the Chesapeake and Delaware Canal and the numerous sand and gravel pits in the Pleistocene deposits, the sedimentary rocks are very poorly exposed in Delaware.

Piedmont Crystalline Rocks

The Piedmont crystalline rocks (Figure 2) are the oldest rocks in the State and are of complex igneous and metamorphic origin. Ward (1959) contains a discussion of these rocks, particularly those of the Wilmington Complex.

Delaware Piedmont rocks have been assigned to the Lower Paleozoic Era and have been divided into the Glenarm Series (Knopf and Jonas, 1922) and the Wilmington Complex (Ward, 1959). The Glenarm Series is further subdivided into the Cockeysville Marble and the Wissahickon Formation. Some pegmatite dikes intrude the Wissahickon and serpentine is found locally near Hoopes Reservoir. The Wilmington Complex is subdivided by Ward (1959) into "amphibolites," "gabbros," "banded gneisses" and some "granites."

The Wissahickon Formation is a biotite-quartz-plagioclase feldspar schist with migmatite zones. The formation generally strikes northeast and dips to the southeast. These rocks are jointed and fractured to some extent. John C. Miller, Delaware Geological Survey, interpreted lineations seen on aerial photographs to be the traces of inclined, tabular, fracture zones that strike essentially northwest (personal communication). Miller interpreted these fracture zones as the result of extensional forces due to regional uplift.

The Cockeysville Marble consists of granular, friable marble seen in outcrop only in a few places north of Newark. It may be fractured and may contain

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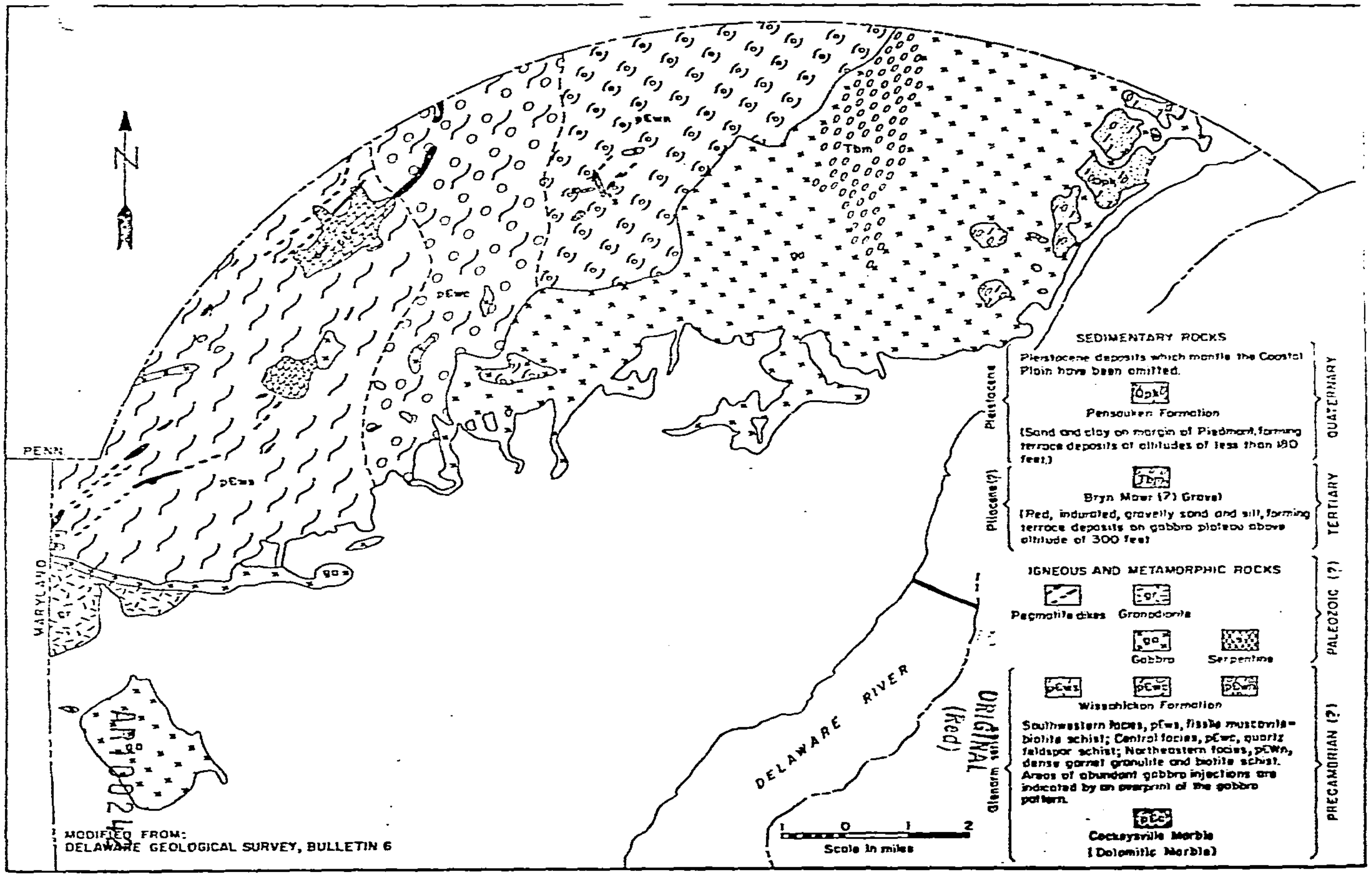

FIGURE 2 GEOLOGIC MAP OF THE PIEDMONT PROVINCE IN NEW CASTLE COUNTY.

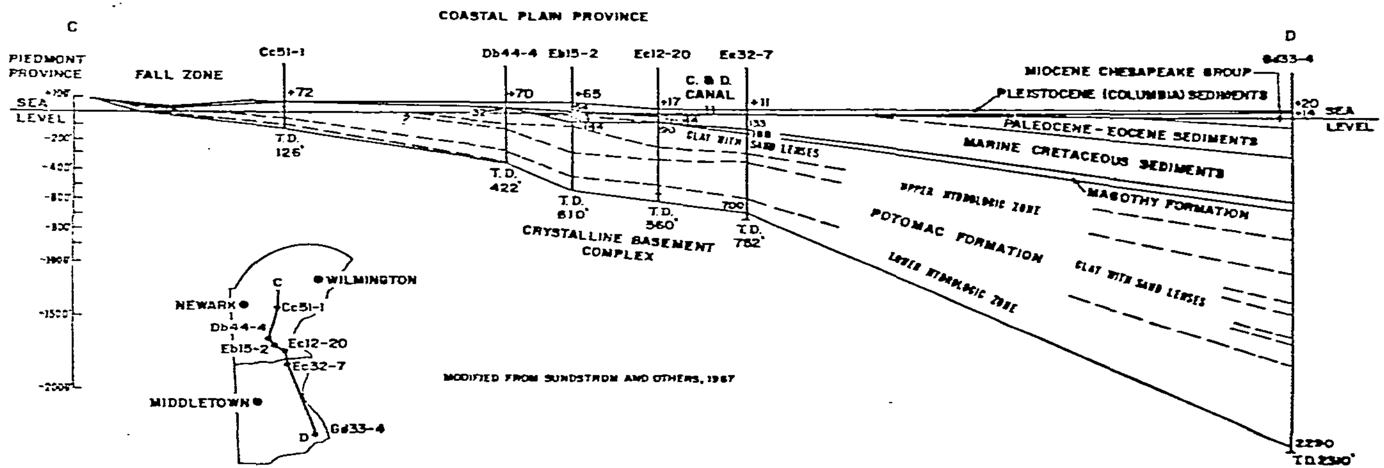

FIGURE 3 GEOLOGIC CROSS SECTION OF NEW CASTLE COUNTY.

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solution cavities at depth.

The Wilmington Complex, still not adequately studied, is a dense gray rock that is occasionally banded. No rigorous study has been made since that of Ward (1959).

South of the Fall Zone, which roughly follows the line of the Kirkwood Highway between Newark and Wilmington, the Piedmont rocks continue, dipping down beneath the sediments of the Coastal Plain to form the crystalline basement (Figures 4 and 5).

Iron Hill and Chestnut Hill, just south of Newark, are outliers of Piedmont rock (mostly gabbro) south of the main Piedmont area. They are entirely surrounded by Coastal Plain sediments.

Coastal Plain Sedimentary Rocks

The distribution of Coastal Plain sedimentary rocks is shown by Table 2. Maps in the Coastal Plain section of this report were prepared from preexisting descriptive logs, geophysical logs and well cuttings. All elevations on the maps are in feet relative to sea level.

Important early work on these rocks in Delaware was done by Clark and others (1896, 1907, 1911, 1918). Definitive work on the Cretaceous done by Groot, Organist, and Richards (1945, 1961, 1968) added much to our understanding of these rocks.

Potomac Formation

Crystalline rocks of the Piedmont are overlain in the Coastal Plain by the Cretaceous nonmarine Potomac Formation. The Potomac Formation in New Castle

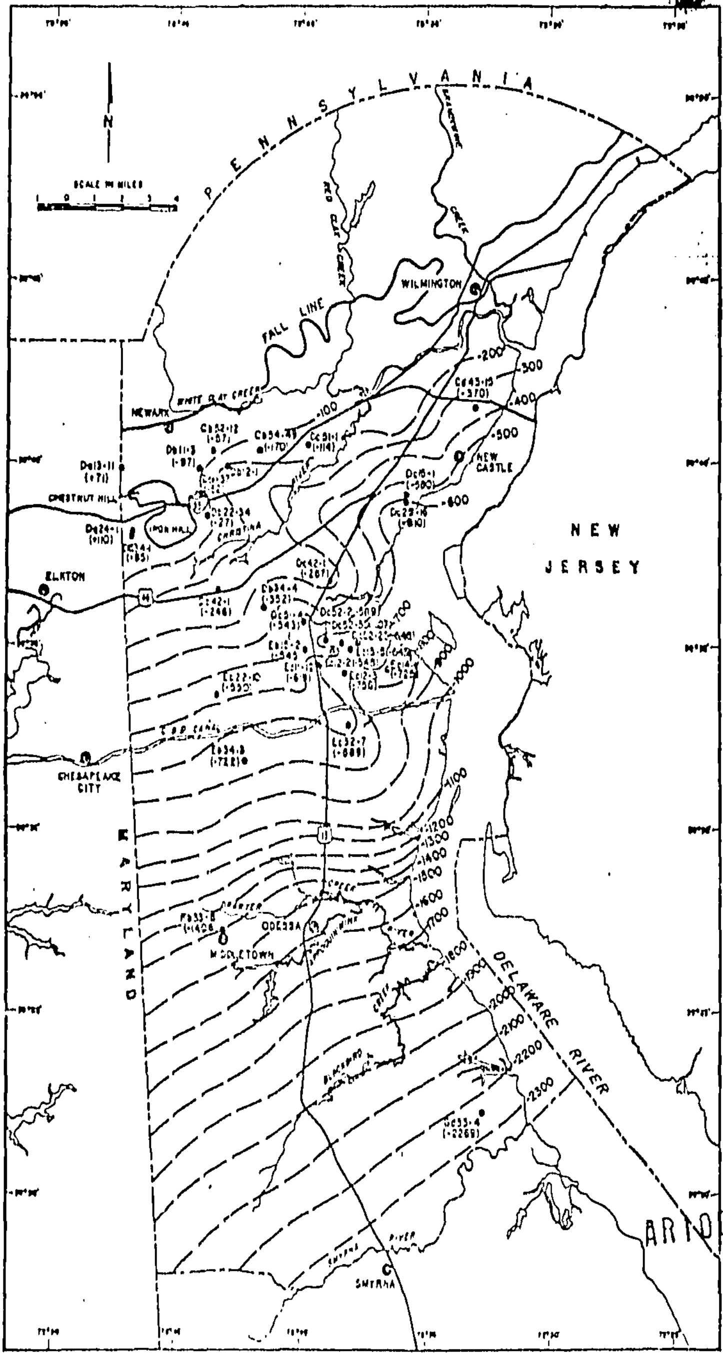

FIGURE 4 STRUCTURAL MAP OF THE TOP OF THE BASEMENT CRYSTALLINE ROCKS.

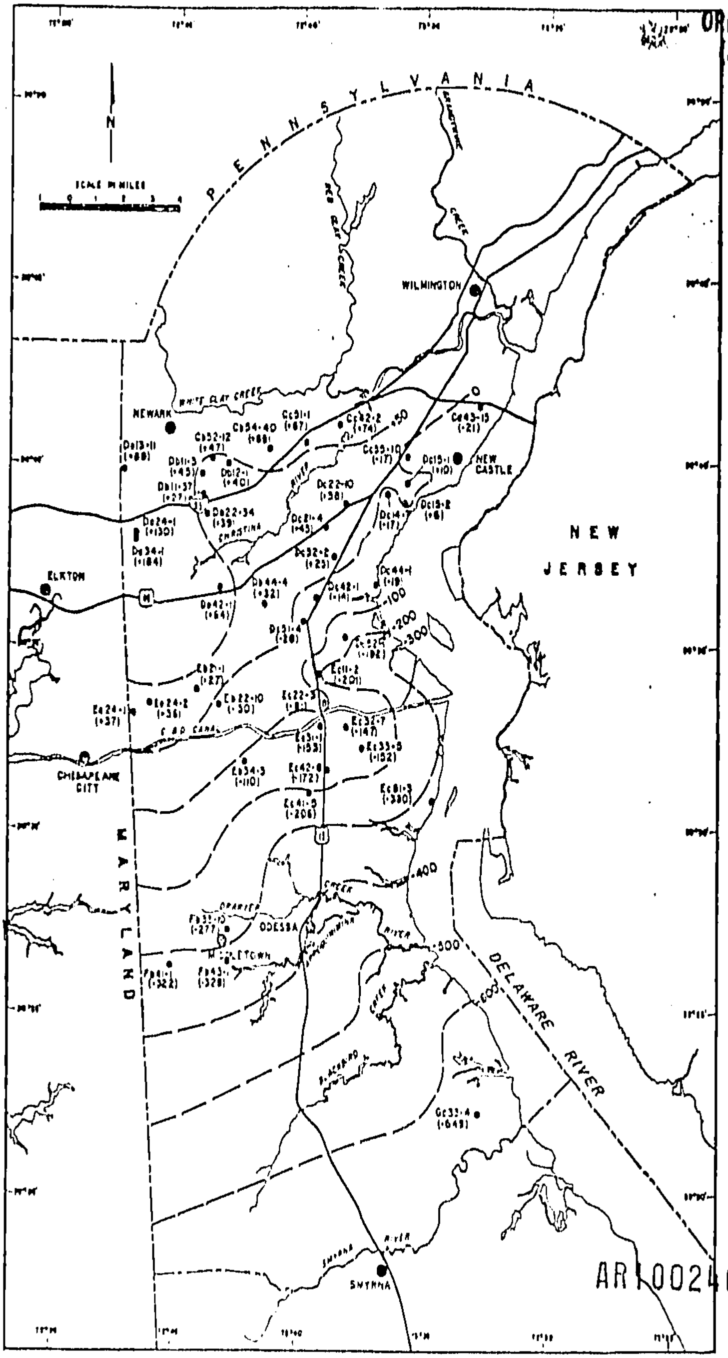

FIGURE 5 STRUCTURAL MAP OF THE TOP OF THE POTOMAC FORMATION.

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County consists of variegated red, gray, purple, yellow and white, frequently lignitic silts and clays containing interbedded white, gray and rust-brown quartz sands and some gravel. Individual beds are usually laterally restricted (Pickett, 1970).

The thickness of these sediments increases southeasterly to more than 1,700 feet in southern New Castle County (Figures 3 and 6). In the northern Coastal Plain Potomac sediments are unconformably overlain by the much younger Columbia Formation (Pleistocene); however, in the Chesapeake and Delaware Canal area and south, the Potomac is overlain by Upper Cretaceous and younger rocks (Figure 1). The maximum depth to the top of the Potomac in southeastern New Castle County is 649 feet (Figure 4). Thicknesses of Potomac sands in parts of New Castle County are shown in Figure 7.

Jordan (1968) studied the distribution of the channel-like sand bodies in the Potomac Formation. He developed an experimental approach in which well logs of the Potomac area are correlated by using basement as the datum plane and by calculating the proportions of sand or clay at intervals above basement datum. Jordan (1968) believed that this provides an indication of the variations in sand and clay content of the sediment supplied to the basin during Potomac time. Jordan stated:

> "The resulting graph (Figure 8) of the proportion of wells containing sand plotted against distance above basement appears to be compatible with what is known of the geology and hydrology of the Potomac Formation in Delaware."

In summary Jordan (1968) stated:

> "The experimental method outlined is considered preliminary, but is thought to have some potential. It resulted from a pressing practical need and was found to be useful as an additional line of evidence in a major hydrologic investigation. The results are reasonable in comparison with the hydrologic results of Sundstrom et. al. (1967). Higher effective coefficients of transmissibility are found in the lower part of the

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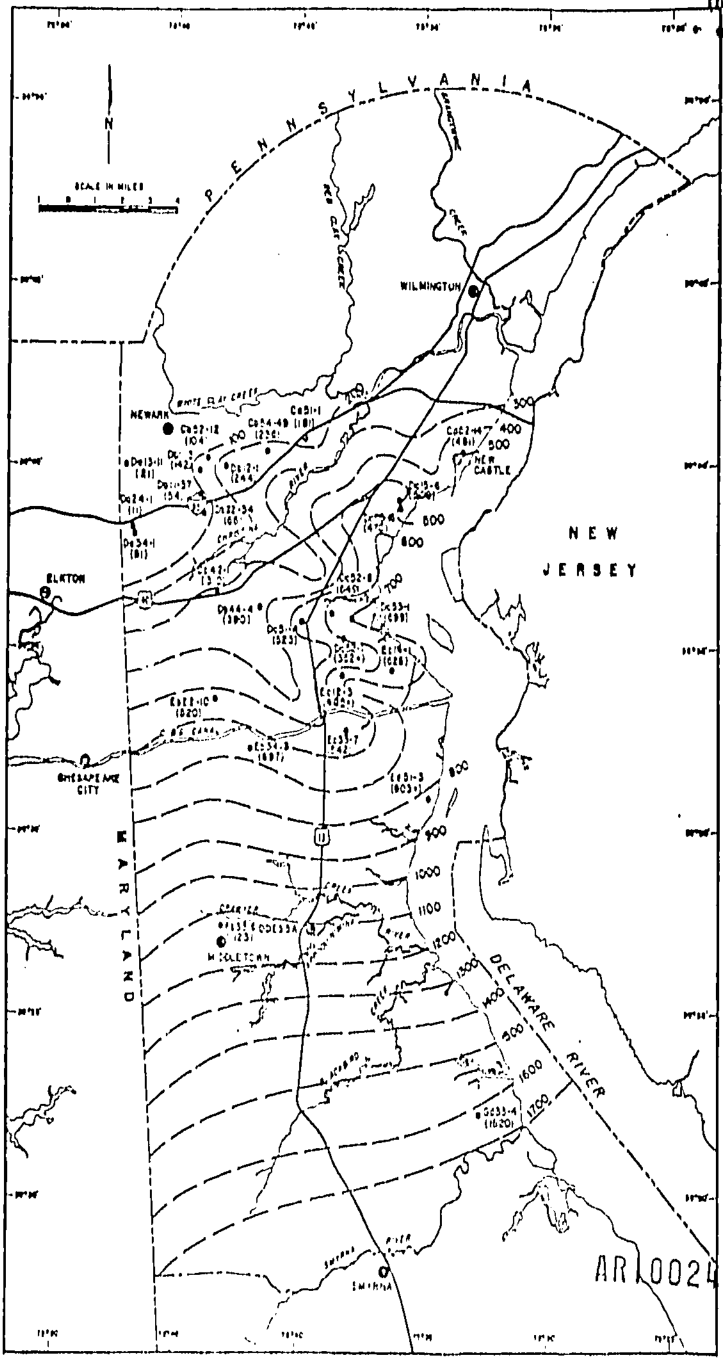

FIGURE 6 MAP OF THE THICKNESS OF THE POTOMAC FORMATION.

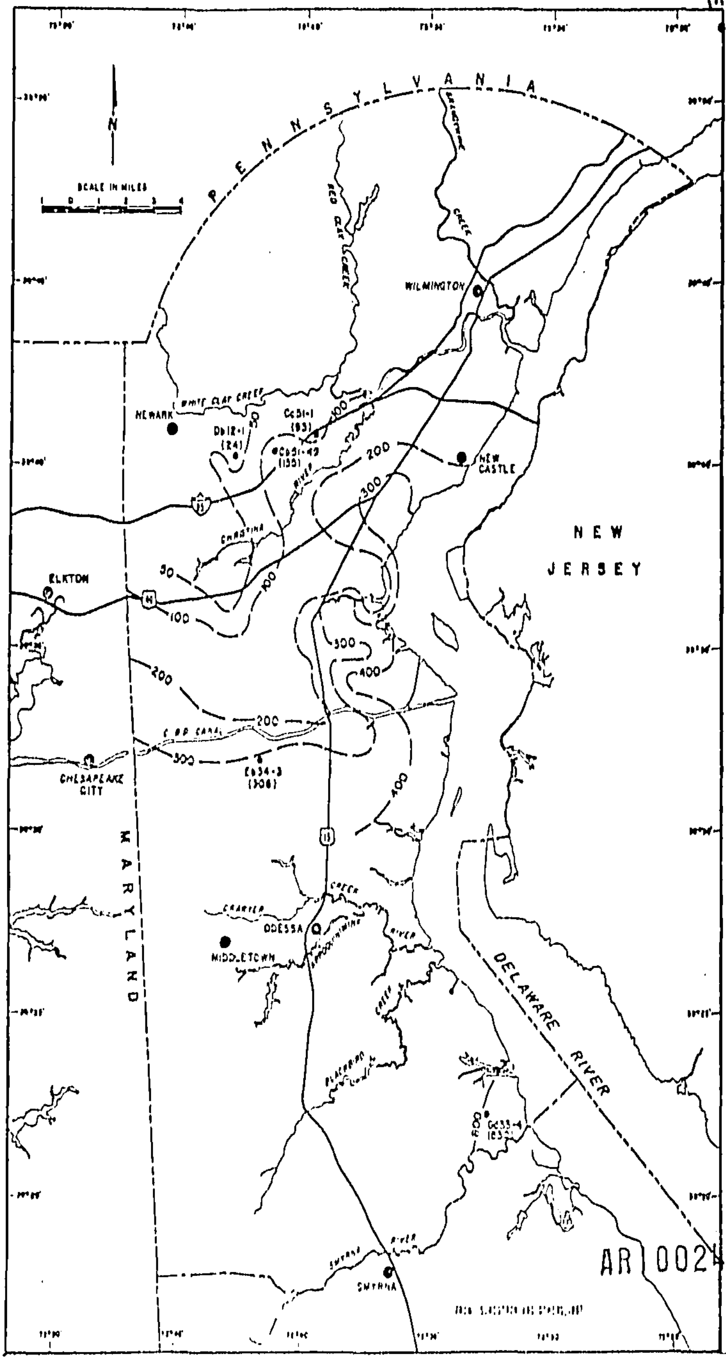

FIGURE 7 MAP OF THE THICKNESS OF THE POTOMAC SANDS.

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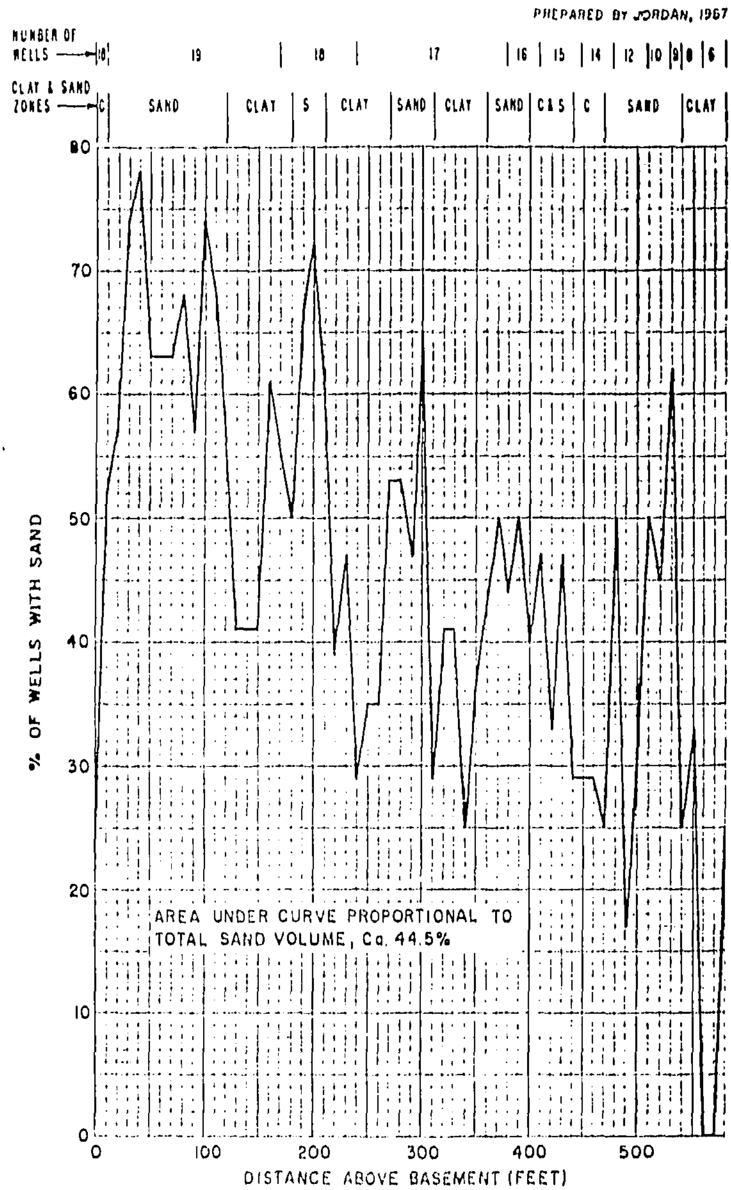

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FIGURE 8 DISTRIBUTION OF SANDS WITHIN THE POTOMAC FORMATION.

> Potomac than in the upper sands by the hydrologists, which agrees with the proportions of sand and clay shown in Figure 2 [Figure 8 in this report]. The definite, but leaky barrier (Sundstrom et. al., 1967) between the two major aquifers in the Potomac has been determined to be the clay-rich zone between about 210 feet and 270 feet above basement (Figure 8) on the basis of well correlation guided by the chart. The chart has served to enable the assignment of wells not otherwise correlatable to the upper of lower ground-water reservoirs. The chart has been tested against electrically logged wells that were not in the sample used in its computation and has yielded encouraging results. Finally, the statistical summary is capable of logical geologic interpretation that is consistent with Groot's (1955) analysis of the deposition of the Potomac."

Columbia Formation

The "Columbia Formation" is the name applied to Pleistocene sediments in New Castle County. Together with the Holocene (Recent) sediments these two comprise the Quaternary Series. The Holocene sediments in New Castle County are in the wetlands near the river and flood plains of inland streams.

The Columbia Formation consists of orange, tan, and yellow medium to coarse sands and gravel. The thickness is shown on Figure 15. Because there is little or no information on the thickness of the Pleistocene or Holocene in wetlands areas, these areas are left blank on the map or are highly generalized. The Columbia sediments are separated by an erosional unconformity (Spoljaric, 1970) from the underlying Cretaceous and Tertiary surface.

According to Spoljaric (1967) the Columbia sediments were deposited by Pleistocene streams which formed a system of straight channels in the area north of the Canal and a braided system south of the Canal. The size of sedimentary particles shows a somewhat systematic decrease in the down current (southward) direction (Jordan, 1964).

Spoljaric and Woodruff (1970) made a comprehensive study of the geology and hydrology of the Columbia Formation in the Middletown-Odessa area. The area was chosen for a pilot study because it contains well developed channel deposits. Spoljaric and Woodruff (1970) state:

> "At the onset of the Columbia sedimentation the greensand valleys were probably first deepened by eroding streams and hills were lowered by denudation. Filling of the valleys followed, with interruptions, until the Rancocas topography was completely covered with the Columbia sediments; the result was a flat, almost featureless surface.
>
> "The deposition of the sediments occurred in channels, flood plains, cut-off meanders, and levees. However, it is often difficult to recognize these various environments, particularly in the subsurface. Conditions of deposition ranged from those present in channels of high-velocity and high-competency streams to those of a tranquil environment. Most of the sediments were brought into the area and deposited there as a part of the sediment load of the streams; however, some large boulders, scattered throughout the area of study, are believed to have been transported by ice floes and similar means, independently of the stream loads.
>
> "The channels of the Pleistocene streams are shallow and rarely exceed 1/2 mile in width. These channels are either straight or meandering and they seem to have formed a braided stream system."

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GROUND-WATER HYDROLOGY

The application of ground-water hydrology has been made in the quantitative assessment of the available water from the Upper and Lower ground-water aquifers of the Potomac Formation in the Midvale-Llangollen Estates area. A considerable amount of hydrologic analyses that follow is based on pumping tests from which data concerning transmissive and storage properties of the aquifers have been determined. The pumping tests have been examined by the Theis nonequilibrium formula and modifications of it as described by Theis, 1935, and Ferris and Knowles in 1962. The formula, in its original and modified forms, uses the coefficients of transmissibility and storage to compute the decline in artesian pressure at given distances from a pumped well at given times after pumping started. The formula provides a means of predicting the decline in artesian head within the cone of influence of a pumped well at any time after pumping started. The formula is based on ideal aquifer conditions, among which it is assumed that the aquifer is homogenous, isotropic, has infinite areal extent and receives no water from vertical leakage. These characteristics, of course, can never be found to be fulfilled completely in the aquifers and in some cases corrections for hydrologic boundaries must be applied in using the equation. Hydraulic boundaries may be of the positive or recharge type, such as the proximity of the outcrop of an aquifer, supplying recharge from rainfall, or a nearby surface stream or lake as a line source of water. Other boundaries may be of the negative or barrier type. Furthermore, vertical permeabilities of the materials forming the confining beds of the aquifer may allow recharge to the aquifer by vertical movement of water. This effect on

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the pressure cone is often much greater at distances from the pumped well because of the greater surface area through which vertical movement can take place. Substantial amounts of vertical leakage can usually be detected in plotting the water level and time data from pumping tests.

The theory and application of hydrologic boundaries and images are discussed by Knowles in U. S. Geological Survey Water Supply Paper 1536-E, 1962, and in several recent text books and papers on hydrology.

The Use of Water

The use of water in the Midvale-Llangollen Estates area in 1972 is estimated to have averaged about 6,700,000 gallons a day, with peak use reaching about 8,700,000 gallons a day. Based on pumpage reported by Marine and Rasmussen, 1955, the pumpage has increased about seven fold in 20 years. Most of the increase in pumping has been by the Amoco Chemical Plant and the Artesian Water Company. The estimated use of water by source is given in Table 3.

Selected Wells in the Potomac Formation in Northern New Castle County

Selected wells drawing water from the Potomac Formation in northern New Castle County are shown and identified on the map in Figure 9. The depth of the well, the water level in the well referred to its mean sea level, the date of the measurement and the altitude of land surface at the well are given in Table 4. The data on the Potomac Formation wells are from the Delaware Geological Survey.

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Table 3

Estimated Use of Water in the Midvale-Llangollen
Estates Area in 1972

User	Source	Estimated Use in Gallons a Day	Remarks
Amoco Chemical Co.	Lower Potomac Aquifer	400,000	Includes Amoco Film Plant--now Crown-Zellerbach
do	Upper Potomac Aquifer	2,000,000	
Artesian Water Co. Llangollen Well Field	do	3,500,000	Peak demand 5,200,000
Artesian Water Co. Midvale-Pleasanteville	Columbia-Potomac Water-Table Aquifer	700,000	
Private & Industrial	Upper Potomac Aquifer and Columbia-Potomac Water-Table Aquifer	125,000	
	Total	6,725,000	

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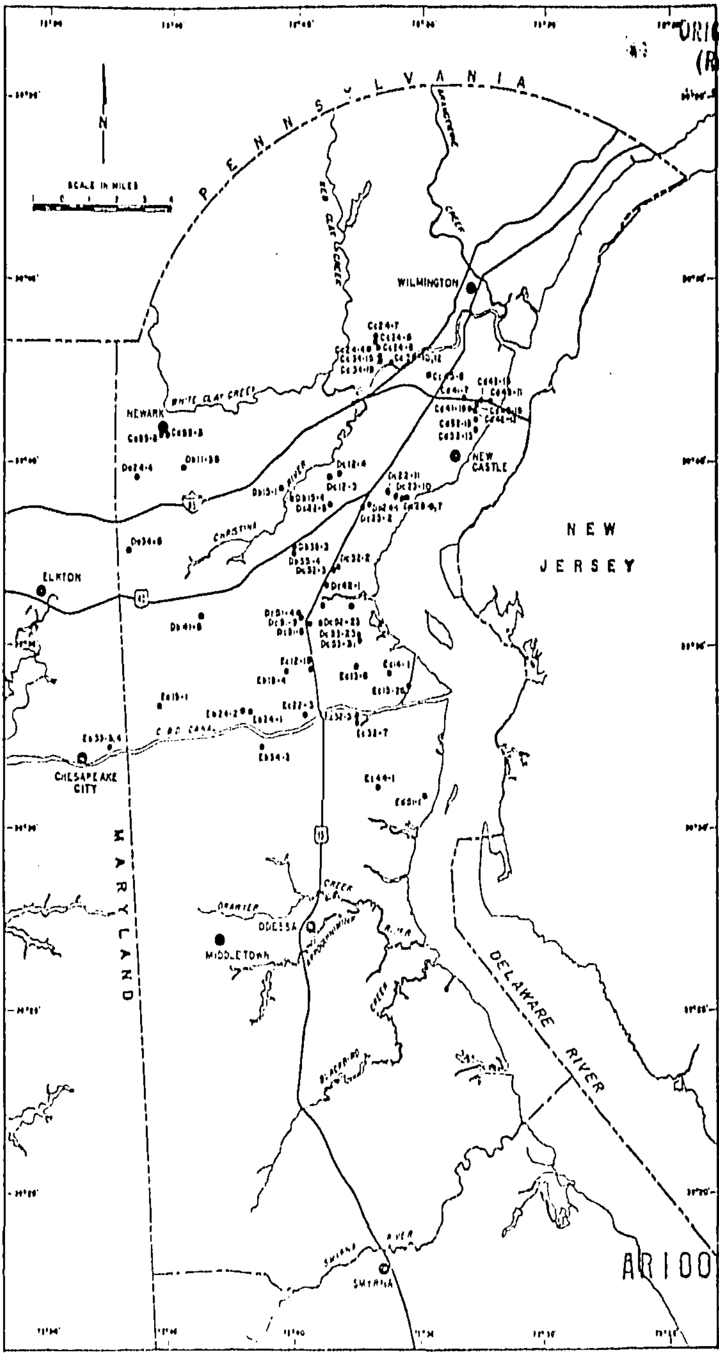

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FIGURE 9 MAP OF SELECTED WELLS IN THE POTOMAC FORMATION.

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Table 4

Records of Wells Drawing Water from the
Potomac Formation in New Castle County, Delaware

Delaware Geological Survey Well Number	Local Well Number	Depth in Feet	Screened	Water Level Ft ± Mean Sea Level	Date of Measurement	Altitude of Ground Surface in Feet
Ca55-3		64.5		80	2-29-52	109
Ca55-8		42		81	7-12-53	105
Cc24-5	Artesian Water Company #17	160		-12	3-22-50	75
Cs24-7	Artesian Water Company #20	163		0	3-24-50	76
Cc24-8		140		-22	3-24-50	70
Cc34-15		112		8	12-7-53	23.3
Cc45-5		302	278-288	-14	7-51	65
Cd41-7		200	189+	0	7-55	65
Cd41-18		80		43	3-18-61	69
Cd42-13		73		19	11-53	40
Cd43-11		88		-21	4-16-52	13.2
Cd52-13		132	116-134	5	8-20-52	12
Cd52-15		73		19	11-53	40
Db11-38		192		52	3-12-64	75±
Db15-1		136		27	1951	30
Dc51-9	Getty #R4	340	252-270, 286-312	21	11-30-55	40.3
Dc53-7	Getty #12	657	534-539	16	9-20-54	54.9
Dc53-23	Getty #5C	710	538-543	8	9-16-54	32.2
Dc53-31	Getty #5A	613	400-406, 201-207	12	7-19-54	32.0
Ea15-1		55		62	11-27-53	65
Ea33-1	Goodrich TW #2	427	390-410	2	11-18-66	60
Ea33-2	Goodrich Obs #1	431	408-418	0	11-18-66	60
Ea33-3	Goodrich Obs #2	431	398-408	2	11-18-66	60
Ea33-4	Goodrich TW #1	695	580-585, 598-603	2	9-30-66	60

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Delaware Geological Survey Well Number	Local Well Number	Depth in Feet	Screened	Water Level Ft ± Mean Sea Level	Date of Measurement	Altitude of Ground Surface in Feet
Eb15-2	Getty #8	636	240-245	26	10-13-54	65.5
Eb15-4	Getty #P3	556	510-541	14	10-25-55	69.5
Eb24-1		208		9+	10-19-43	60+
Eb24-2		177		21	8-52	45
Eb34-3		845	442-462	-2	4-20-67	58.2
Ec11-2	Getty #7	565+	560-565	+19.64	1955	41.5
Ec12-15	Getty #3B	734	340-345	10	9-19-54	57.5
Ec12-20	Getty #P9	558	525-558	-14	4-56	13±
Ec13-6	Getty #16	705	523-563, 581-592	4	1-5-55	35.5
Ec14-1	Getty #13	757	678-685	6	9-20-54	4.4
Ec15-26		701	631-636, 675-695	-44±	4-12-61	10±
Ec22-3		261-	235-260	13	2-16-53	10
Ec32-3	Union Carbide TW #2 (Site 1)	420	318-328, 338-348		1966	
Ec32-7	Union Carbide TW #1 (Site 1)	752	586-596	-33	1966-67	11.15
Ec44-1		350		6	3-50	25
Ed51-1		473	447-473	6	1-20-56	11

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Specific Capacity and Yield of Wells in the
Midvale-Llangollen Estates Area

The specific capacity of a well may be defined as the amount of water yielded in gallons a minute per foot of drawdown of the water level in the well determined after a stated period of pumping in hours. Assuming that a well has been properly designed, properly constructed and properly developed, the specific capacities give clues not only to the amount of water that can be developed from the well, but also to the hydrology of the ground-water reservoirs from which the well obtains water. If a well meets all of the criteria of good design, construction and development and is highly efficient when pumped, then there is a definite relation of well diameter, specific capacity of the well and the coefficients of transmissibility and storage in the aquifer. This relationship has been illustrated graphically by Meyer (1963) and is shown in Figure 10.

The specific capacity of one well, PW-1, in the Lower Potomac aquifer in the Amoco Polymer Plant well field was determined from a pumping test conducted by Leggette, Brashears and Graham on October 24-25, 1960, to be three and three tenths gallons a minute per foot of drawdown after 24 hours of pumping. The well was pumped at a rate of 225 gallons a minute with a drawdown of 68.4 feet after 24 hours of pumping. Sundstrom and Pickett, 1971, list 10 specific capacities determined in wells to the Lower Potomac aquifer in the Chesapeake and Delaware Canal area. The specific capacities ranged from nine tenths to seven gallons a minute per foot of drawdown and averaged two and eight tenths gallons a minute per foot of drawdown.

The specific capacities of wells obtaining water from the Upper Potomac aquifer at the Llangollen Estates well field of the Artesian Water Company and

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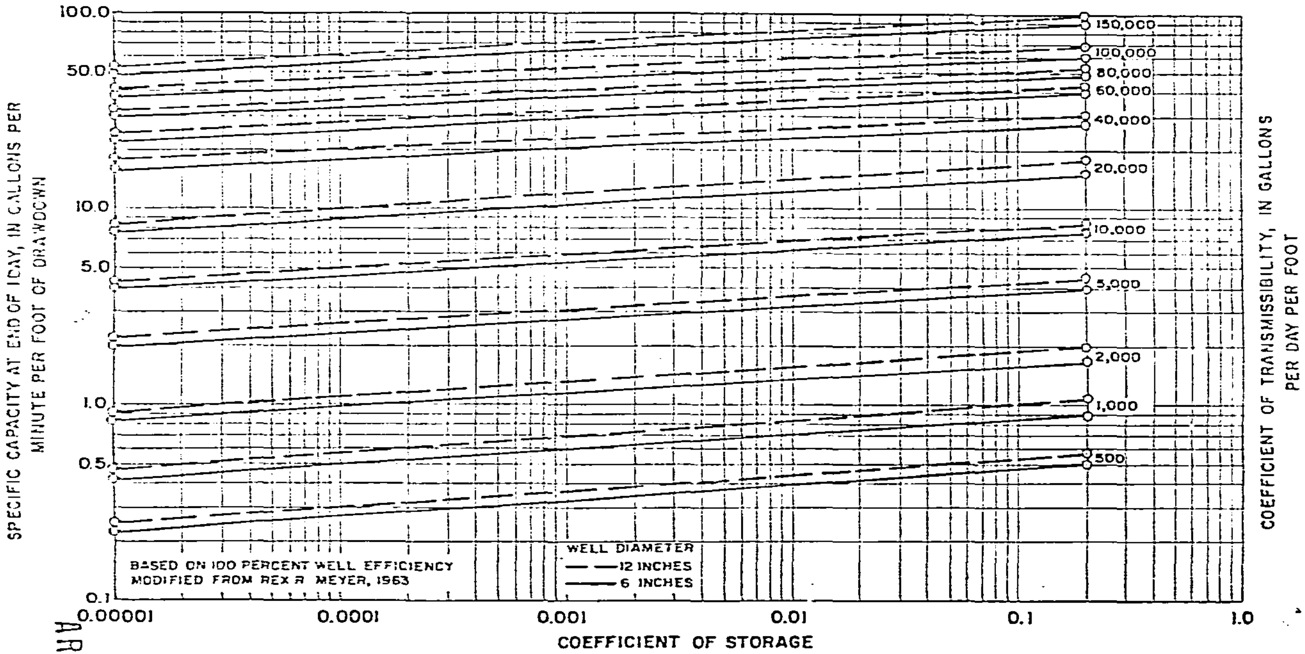

FIGURE 10 RELATION OF WELL DIAMETER, SPECIFIC CAPACITY, TRANSMISSIBILITY AND COEFFICIENT OF STORAGE

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at Amoco well PW-3 vary widely from well to well, ranging from eight and five tenths to 25 gallons a minute per foot of drawdown. Table 5 gives the specific capacities of seven wells drawing water from the Upper Potomac aquifer in the Llangollen Estates and the Amoco Polymer Plant well fields. The range in specific capacities attests to the fair to good water-yielding properties of the wells and demonstrates the range in water-yielding properties of wells within relatively short distances from each other.

The specific capacity of a well not only controls the amount of water that can be developed from a well, but also affects the amount of power required to pump a given quantity of water. The specific capacity of well E-2 is nearly three times greater than the specific capacity of E-1 and will require only about one third the power required to pump the same amount of water from well E-1.

The Artesian Water Company has two wells reported in Bulletin 4 of the Delaware Geological Survey which, according to their driller's log, appear to be in the subcrop of the Upper Potomac aquifer. These wells are both located at Midvale. The yields of the wells are reported to be 475 gallons a minute from one well and 365 gallons a minute from the other. The larger yielding well is reported to have a specific capacity of 15.8 gallons a minute per foot of drawdown. The driller's log of one of the wells published in Bulletin 4 indicates that the well is drawing water from the Pleistocene and subcropping sands of the Upper Potomac aquifer.

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Table 5

Specific Capacity of Wells in the Upper Potomac Aquifer
in the Midvale - Llangollen Estates Area

Owner	Well	Yield (gpm)	Drawdown (ft)	Hours Pumped	Specific Capacity (gpm/ft)	Remarks
Artesian Water Co.	E-1	400	47.0	24	8.5	Pumping Test March 1971
	E-2	600	24.0	24	25.0	Pumping Test July 22, 1972
	G-3	500	56.0	24	8.9	Pumping Test, November 23, 1971
	J-1	608	36.0	24	16.9	Pumping Test, December 17,1971
	K-1	600	69.5	24	8.6	Pumping Test
	1	656	24.79	8	24.4	Test by Layne-New York Co. January 13, 1969
Amoco Plant	PW-3	805	41.0	24	19.6	Pumping Test May 31,1961 Leggette, Brashears and Graham

Source of Data: Delaware Department of Natural Resources and Environmental Control, Division of Environmental Control.

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Transmissibility of the Aquifers in the
Midvale-Llangollen Estates Area

Transmissibility as expressed herein, may be defined as the amount of water that will pass through a strip of the aquifer one foot wide in one day having the saturated height of the aquifer under a hydraulic gradient of 100 percent. Transmissibility in the Midvale-Llangollen Estates area has been determined from one pumping test in the Lower Potomac aquifer and six tests in the Upper Potomac aquifer. No determinations of transmissibility have been made from tests of the Pleistocene aquifer in the immediate area.

The transmissibility of the Lower Potomac aquifer, based on a pumping test conducted by Leggette, Brashears and Graham, October 24-25, 1960, on well PW-1 in the Amoco Polymer Plant well field is very low. The transmissibility of the aquifer is about 2,000 gallons a day per foot which is a low value for the Potomac aquifer.

Six pumping tests in the Upper Potomac aquifer have been analyzed to determine the transmissibility of the Upper Potomac aquifer in the Midvale-Llangollen Estates area. The transmissibilities ranged from 26,400 to 41,700 and averaged 36,400 gallons a day per foot. The results of these tests are given in Table 6. The pumping tests were conducted over a period of 24 hours at each well (see Figures 11, 12, 13 and 14). In the Chesapeake and Delaware Canal area pumping tests by the Getty Oil Company well field (formerly Tidewater) were conducted by Leggette, Brashears and Graham in 1954 and 1955. A pumping test was conducted in the Lower Potomac aquifer for 17 days and in the Upper Potomac aquifer for seven days. The results of these tests were reported in Sundstrom and others, 1967. The tests in the Getty well field reveal that the effective transmissibility in both the Upper and Lower Potomac aquifers is reduced in time by

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Table 6

Transmissibility of the Upper Potomac Aquifer in the Llangollen Area

Well	Test By	Date	Computed By	Transmissibility GPD/FT
Amoco PW-3	Leggette, Brashears & Graham	June 1961	R.W. Sundstrom	38,600
Artesian Water Co. 1	Layne-New York Co.	Jan. 13, 1969	R.W. Sundstrom	38,500
Artesian Water Co. G-3		Nov. 23, 1971	R.W. Sundstrom	33,000
Artesian Water Co. K-1		Jan. 1972	R.W. Sundstrom	41,700
Artesian Water Co. J-1		Dec. 17, 1971	R.W. Sundstrom	38,400
New Castle County RW-4	Mike Apgar, Roy F. Weston, Inc.	Nov. 6, 1973	R.W. Sundstrom	26,400

Average transmissibility of six tests 36,100 gallons per day per foot.

GPD/FT Gallons a day per foot.

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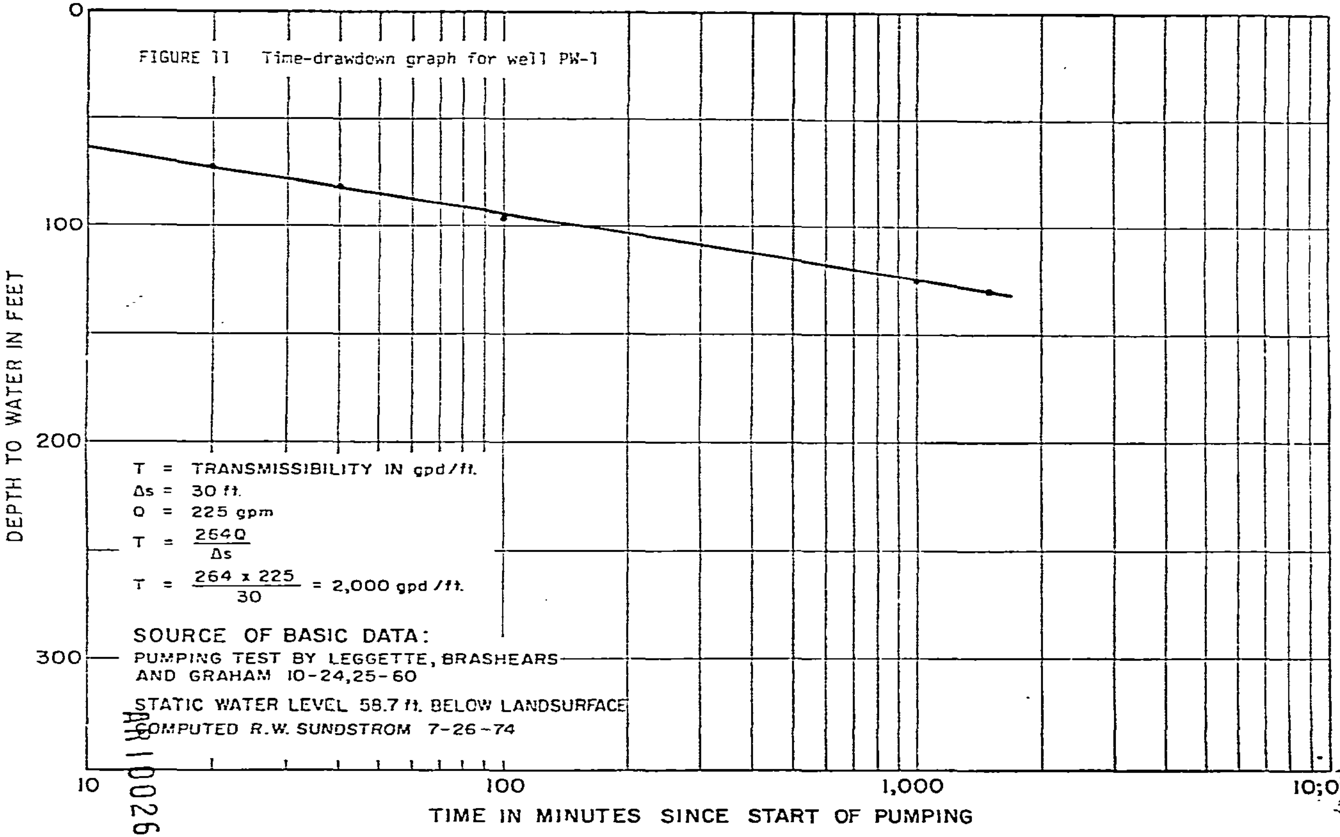


FIGURE 11 Time-drawdown graph for well PW-1

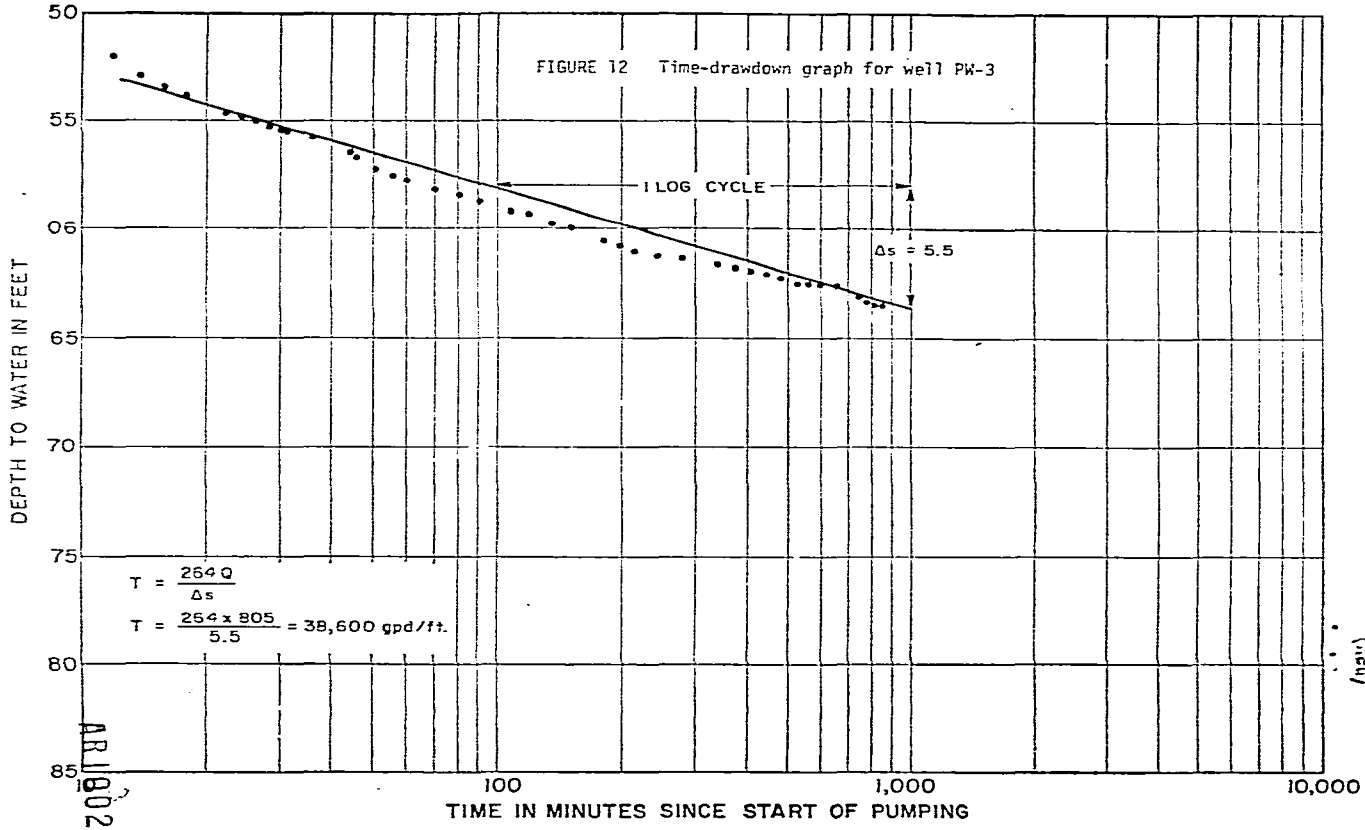


FIGURE 12 Time-drawdown graph for well PW-3
1 LOG CYCLE
Δs = 5.5
$T = \frac{264Q}{\Delta s}$
$T = \frac{264 \times 805}{5.5} = 38{,}600$ gpd/ft.
DEPTH TO WATER IN FEET
TIME IN MINUTES SINCE START OF PUMPING
50
55
60
65
70
75
80
85
10
100
1,000
10,000

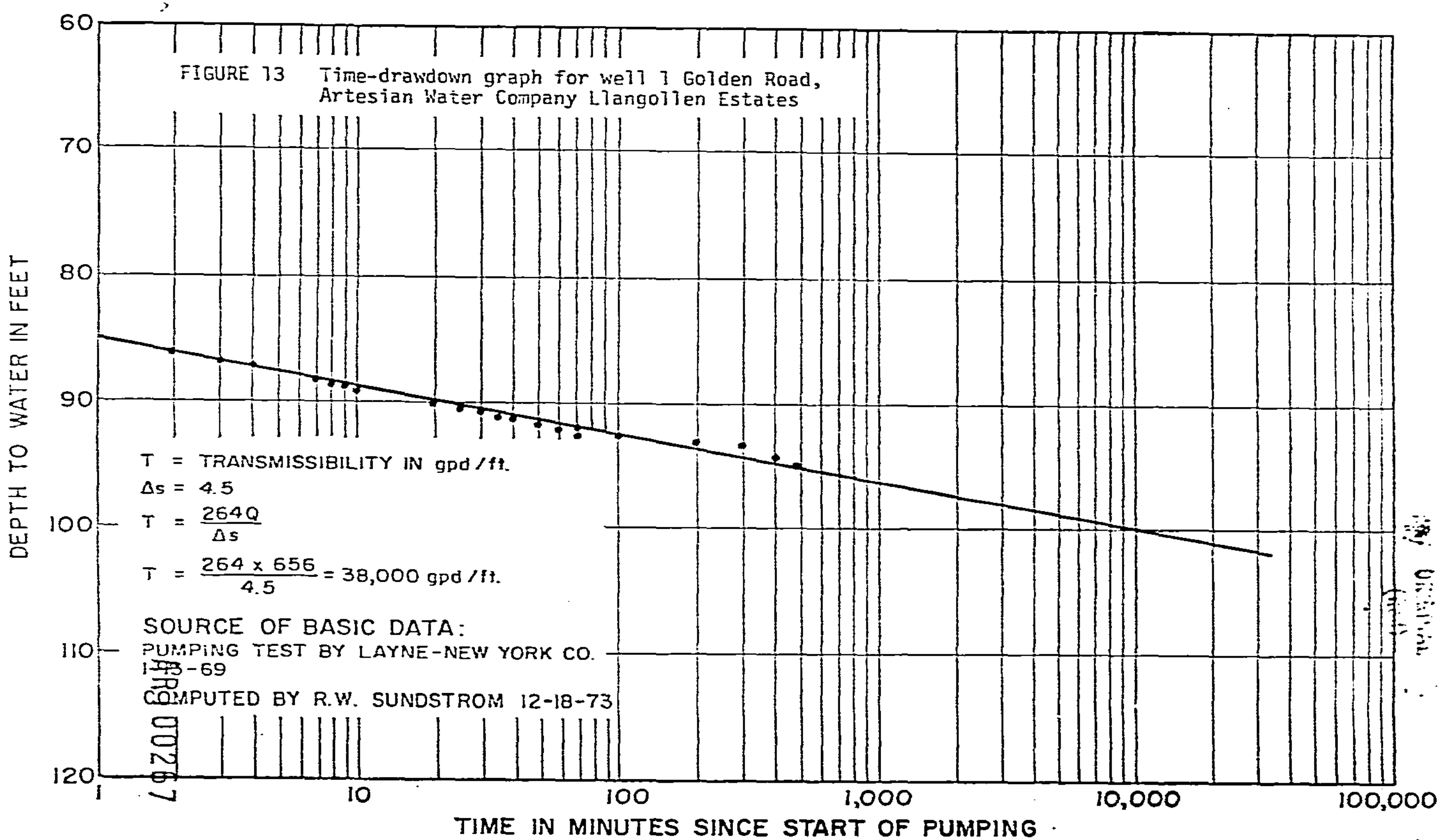
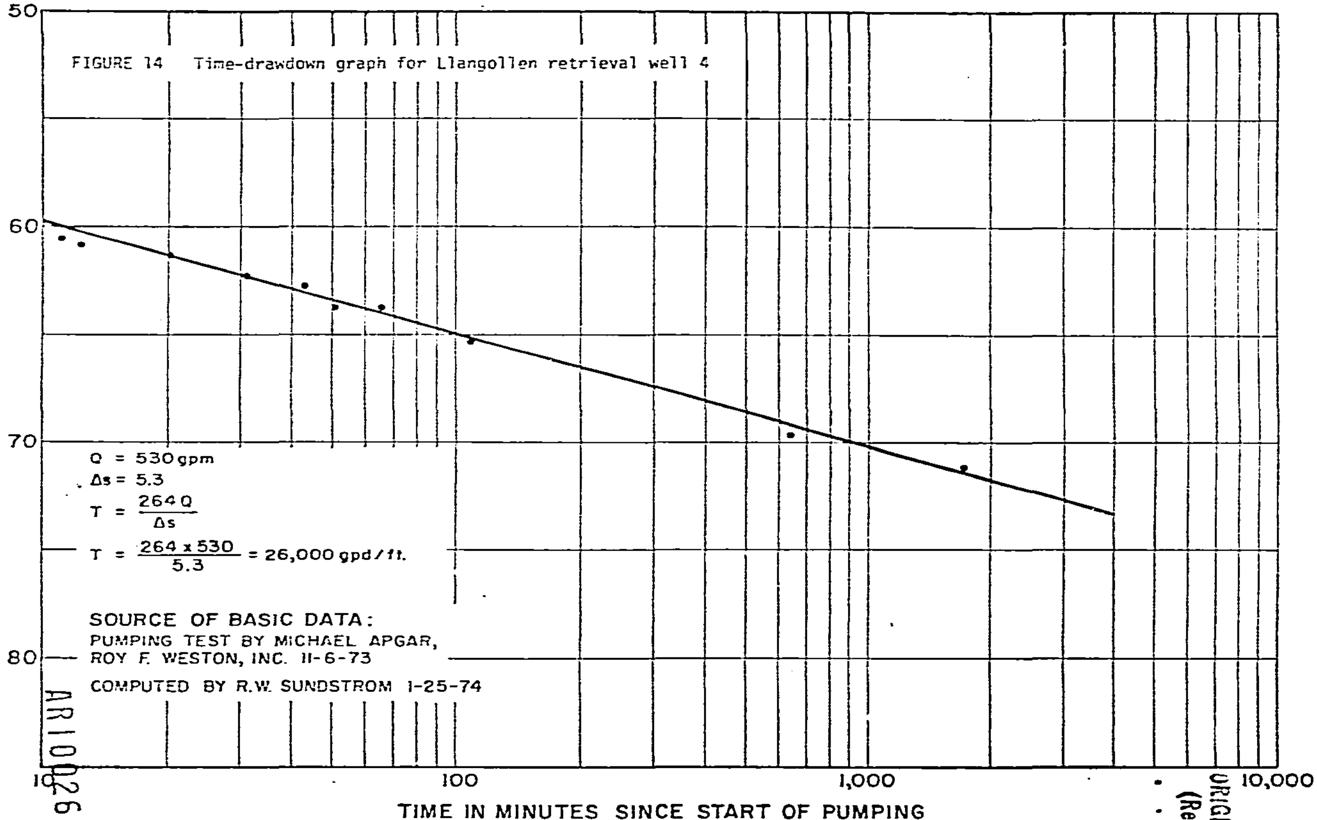


FIGURE 13 Time-drawdown graph for well 1 Golden Road, Artesian Water Company Llangollen Estates

FIGURE 14 Time-drawdown graph for Llangollen retrieval well 4



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geologic boundaries. In some tests significant changes were observed in time-drawdown relation after as much as four days of pumping. In the Midvale-Llangollen Estates area influence by geological boundaries can also be expected from longer periods of pumping. The geologic boundaries will be negative and the recharge boundary will be positive. The proximity of the outcrop, estimated one to four miles away from the Amoco and Artesian Water Company Llangollen Estates well fields, will probably have more effect on the wells by reducing drawdowns with time than will the geologic boundaries in increasing drawdown.

Although determinations of transmissibility of the Pleistocene and subcropping Potomac aquifers have not been made in the Midvale-Llangollen Estates area, the two water-table aquifers are likely to have transmissive properties above 20,000 gallons per day per foot or more where the aquifers have adequate saturated thickness. In some places where the Pleistocene and Upper Potomac subcrop are thick, the transmissibility may reach 40,000 gallons a day per foot or more.

The Relation of Drawdown to Transmissibility and Distance

The relation of drawdown of the water level after 180 days of continuous pumping to transmissibility and distance has been illustrated effectively by Wilson, 1967, in Figure 15. For the Lower Potomac aquifer, the drawdown would be two and a half times as great as that illustrated for a transmissibility of 5,000 gallons a day per foot, as shown in Figure 15. For the Upper Potomac with an average transmissibility of 36,000 gallons a day per foot, the drawdown curve could lie about half way between the curves for transmissibilities of 20,000 and 50,000 gallons a day as illustrated in Figure 15.

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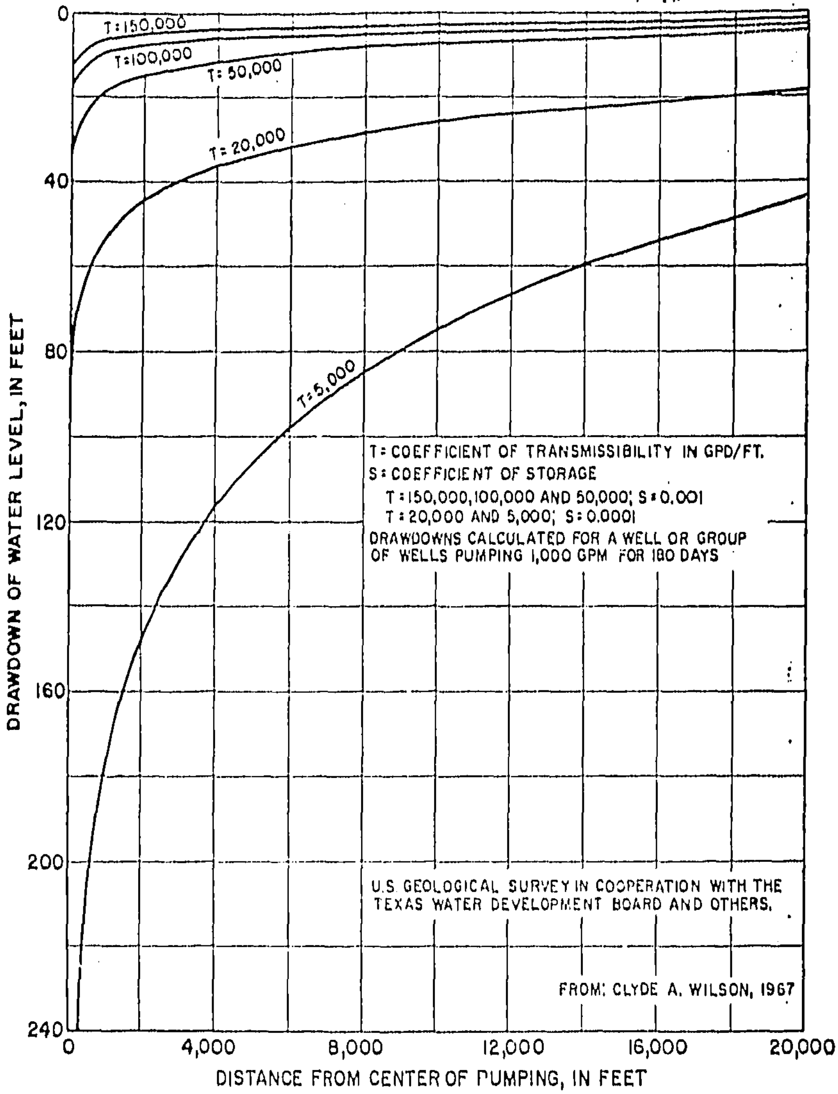

FIGURE 15 RELATION OF DRAWDOWN TO TRANSMISSIBILITY AND DISTANCE.

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Coefficient of Storage in the Upper Potomac Aquifer

The Upper Potomac aquifer at the Llangollen Estates well field of the Artesian Water Company and at the Amoco Polymer Plant well field is tightly confined by a thick strata of dense clay at both well fields. Geraghty and Miller, 1973, reported to the Artesian Water Company a coefficient of storage of 0.0005 for the Llangollen Estates well field. This value is in the same order of magnitude as that found for the Upper Potomac aquifer in the Getty Oil Company well field where the aquifer is also confined by thick clay. In the less confined areas toward the outcrop areas and in the outcrop area of the Llangollen Estates and Amoco Polymer Plant well fields the coefficient of storage will increase greatly and may be in the order of 0.15 in the subcrop. J. G. Ferris and D. B. Knowles of the U. S. Geological Survey (1962) say the following about the coefficient of storage:

> "The coefficient of storage, S, of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.
>
> "A simple way of visualizing this concept is to imagine an artesian aquifer which is elastic and uniform in thickness, and which is assumed, for convenience, to be horizontal. If the head of water in that aquifer is decreased, there will be released from storage some finite volume of water that is proportional to the change in head. Because the aquifer is horizontal, the full observed head change is evidently effective perpendicular to the aquifer surface. Imagine further a representative prism extending vertically from the top to the bottom of this aquifer, and extending laterally so that its cross-sectional area is coextensive with the aquifer-surface area over which the head change occurs. The volume of water released from storage in that prism, divided by the product of the prism's cross-sectional area and the change in head, results in a dimensionless number which is the coefficient of storage. If this example were revised slightly, it could be used to demonstrate the same concept of coefficient of storage for a horizontal water-table aquifer or for a situation in which the head of water in the aquifer is increased.
>
> "As with almost any concise definition of a basic concept, it is necessary to develop its full significance, its limitations, and its

practical use and application through elaborative discussion. The coefficient of storage is no exception in this respect, and the following discussion will serve to bring out a few ideas that are important in applying the concept to artesian and water-table aquifers in horizontal or inclined attitudes.

"Observe that the statement of the storage-coefficient concept first focuses attention on the volume of water that the aquifer releases from or takes into storage. Identification and measurement of this volume poses no particular problem, but it should be recognized that it is measured outside the aquifer under the natural local conditions of temperature and atmospheric pressure; it is not the volume that the same amount of water would occupy if viewed in place in the aquifer.

"Although the example used to depict the concept of the storage coefficient was arbitrarily developed around a horizontally disposed artesian aquifer, the concept applies equally well to water-table aquifers and is not compromised by the attitude of the aquifer. This flexibility of application relies importantly, however, on relating the storage-coefficient concept to the surface area of the aquifer and to the component of head change that is normal to that surface. In turn this relation presupposes that the particular aquifer prism involved in the movement of water into or out of storage is that prism whose length equals the saturated thickness of the aquifer, measured normal to the aquifer surface, and whose cross-sectional area equals the area of the aquifer surface over which the head change occurs. Furthermore, water moves into or out of storage in this prism in direct proportion only to that part of the head change that acts to compress or distend the length of the prism. In other words, the component of the head change to be considered in the release or storage of water is that which acts normal to the aquifer surface. The mathematical models devised for analyzing ground-water flow usually require uniform thickness of aquifer. However, the storage coefficient concept, as defined here, applies equally well to aquifers that thicken or thin substantially, if the "surface area" is measured in the plane that divided the aquifer into upper and lower halves that are symmetrical with respect to flow. The imaginary prism would then be taken perpendicular to this mean plane of flow.

The Artesian Case

"Consider an artesian aquifer, in any given attitude, in which the head of water is changed, but which remains saturated before, during, and after the change. It is assumed that the beds of impermeable material confining the aquifer are fluid in the sense that they have no inherent ability to absorb or dissipate changes in forces external to or within the aquifer. Inasmuch as

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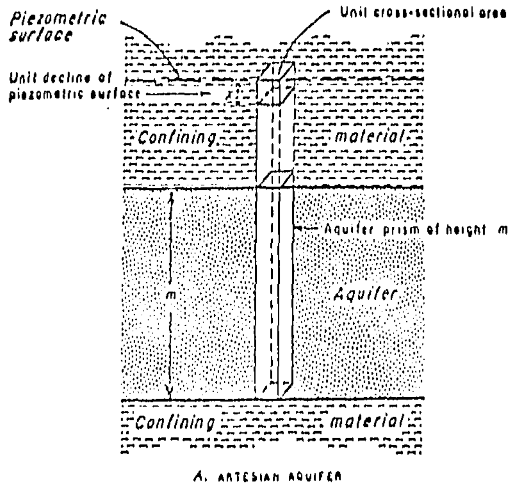

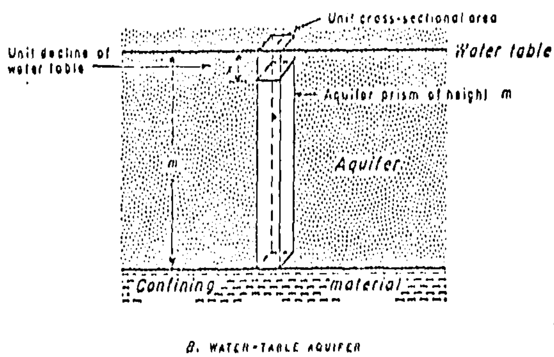

Figure 16 Diagrams for Coefficient of Storage.

From: J. G. Ferris and Others, 1962

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no dewatering or filling of the aquifer is involved, the water released from or taken into storage can be attributed only to the compressibility of the aquifer material and of the water. By definition the term "head of water" and any changes therein connote measurements in a vertical direction with reference to some datum. In a practical field problem the change in head very likely would be observed as a change in water-level elevation in a well. The change in head is an indication of the change in pressure in the aquifer prism, and the total change in force tending to compress the prism is equal to the product of the change in pressure multiplied by the end area of the prism. Obviously this change in force is not affected by the inclination of the aquifer, inasmuch as a confined pressure system is involved and the component of force due to pressure always acts normal to the confining surface. Thus any conventional method of observing head change will correctly identify the change in pressure normal to the aquifer surface and may be considered as a component of head acting normal to that surface.

"Examine Figure 16A, which depicts, in schematic fashion, a horizontal artesian aquifer. Shown within the aquifer is a prism of unit cross-sectional area and of height, m, equal to the aquifer thickness. If the piezometric surface is lowered a unit distance, x, as shown, a certain amount of water will be released from the aquifer prism. This occurs in response to a slight expansion of the water itself and a slight decrease in porosity due to distortion of the grains of material composing the aquifer skeleton.

"Summary statement.--For an artesian aquifer, regardless of its attitude, the water released from or taken into storage, in response to a change in head, is attributed solely to compressibility of the aquifer material and of the water. The volume of water (measured outside the aquifer) thus released or stored, divided by the product of the head change and the area of aquifer surface over which it is effective, correctly determines the storage coefficient of the aquifer. Although rigid limits cannot be established, the storage coefficients of artesian aquifers may range from about 0.00001 to 0.001.

The Water-Table Case

"Application of the storage coefficient concept to water-table aquifers is more complex, though reasoning similar to that developed in the preceding paragraphs can be applied to the saturated zone of an inclined water-table aquifer. Consider a water-table aquifer, in any given attitude, in which the head of water is changed. Obviously there will now be dewatering or refilling of the aquifer, inasmuch as it is an open gravity system with no

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confinement of its upper surface. Thus the volume of water released from or taken into storage must now be attributed not only to the compressibility of the aquifer material and of the water, in the saturated zone of the aquifer, but also to gravity drainage or refilling in the zone through which the water table moves. The volume of water involved in the gravity drainage or refilling, divided by the volume of the zone through which the water table moves, is the specific yield. Except in aquifers of low porosity the volume of water involved in gravity drainage or refilling will ordinarily be so many hundreds or thousands of times greater than the volume attributable to compressibility that for practical purposes it can be said that the coefficient of storage equals the specific yield. The conventional method of measuring change in head by observing change in water-level elevation in a well evidently identifies the vertical change in position of the water table. In other words, head change equals vertical movement of the water table. It can be seen that the volume of the zone through which the water table moves is equal to the area of aquifer surface over which the head change occurs, multiplied by the head change, multiplied by the cosine of the angles of inclination of the water table. The product of the last two factors is the component of head change acting normal to the aquifer surface. The importance of interpreting correctly the phrase "component of head change" which appears in the definition of the storage coefficient cannot be overemphasized.

"Examine Figure 16B, which depicts, in schematic fashion, a horizontal water-table aquifer. Again a unit prism of the aquifer is shown, and it is assumed that the water table is lowered a unit distance, x. Usually the water that is thereby released represents, for practical purposes, the gravity drainage from the x portion of the aquifer prism. Theoretically, however, a slight amount of water comes from the portion of the prism that remains saturated, in accord with the principles discussed for the artesian case.

"Summary statement.--For a water-table aquifer, regardless of its attitude, the water released from or taken into storage, in response to a change in head, is attributed partly to gravity drainage or refilling of the zone through which the water table moves, and partly to compressibility of the water and aquifer material in the saturated zone. The volume of water thus released or stored, divided by the product of the area of aquifer surface over which the head change occurs and the component of *head change normal to that surface, correctly determines the storage coefficient* of the aquifer. Usually the volume of water attributable to compressibility is a negligible proportion of the total volume of water released or stored and can be ignored. The storage coefficient then is sensibly equal to the specific yield. The storage coefficients of water-table aquifers range from about 0.05 to 0.30."

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Vertical Permeability Above the Upper Potomac Aquifer

Vertical permeability of the materials forming the confining beds of the aquifer determines the rate of recharge to the aquifer by vertical movement of water. This recharge is often much greater at distances from the pumped well because of the greater surface area through which vertical movement can take place. Substantial amounts of vertical leakage can usually be detected in plotting the water level and time data from pumping tests. Computations of vertical permeabilities in the Potomac Formation in the Getty Oil Company well field made by Sundstrom and others, 1967, ranged from 0.002 to 0.0007 gallons a day per square foot. The vertical permeabilities in the Artesian Water Company Llangollen Estates and Amoco Polymer Plant well fields where the confining clays are thick are probably within the same range as the Getty well field. The vertical permeability is very low in the Llangollen Estates well field, the Amoco Polymer well field and all areas where the dense clay forming the confining bed of the Upper Potomac is thick and continuous in areal distribution. Low vertical permeability is further assured in the Delaware River flood plain and river bed by the thick section of fine impermeable silts beneath the Delaware River estuary (Figure 17).

Vertical permeability is high in areas where the confining clay is very thin and discontinuous or absent. This condition occurs in the vicinity of part of the Llangollen landfill. The confining clay is absent in test wells 10, 11 and 15 near the landfill. The confining clay may be absent in places in the vicinity of Army Creek where the creek channel in earlier stages of development may have cut through the entire section of the clay and the old stream beds became filled and elevated by coarser material carried and deposited by the stream at a later time. In the subcrop where the Upper Potomac aquifer is

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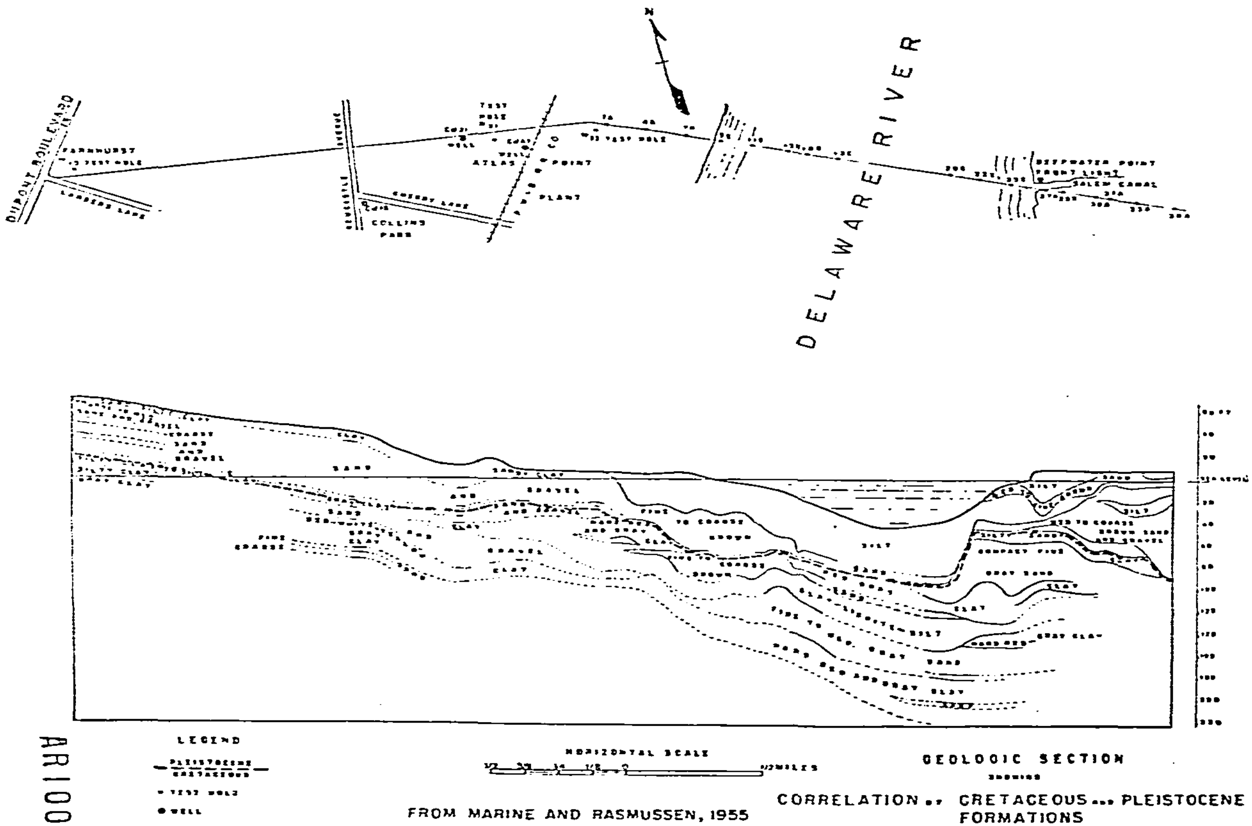

GEOLOGIC SECTION
showing
CORRELATION of CRETACEOUS and PLEISTOCENE FORMATIONS

FROM MARINE AND RASMUSSEN, 1955

FIGURE 17 GEOLOGIC CROSS-SECTION AT DELAWARE MEMORIAL BRIDGE

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in contact with the overlying Pleistocene sands and gravels the vertical permeability is higher and in places may amount to a small to medium fraction of a gallon a day per square foot or more.

Water Levels and Artesian Head in the Midvale-Llangollen Estates Area

Four wells were drilled to the Lower Potomac aquifer in 1915 and 1916 at the Delaware Rayon Company Plant (later Amoco Chemical Company and now Crown-Zellerbach Film Plant). The wells were all finished in both the Upper and Lower Potomac aquifers and no artesian pressure recordings in either of the Potomac aquifers were made at that time. In 1928, 13 years after the wells were put into operation, the artesian head in one well was measured six feet above sea level. This measurement is thought to have been affected several feet by the effect of pumping of the four wells over the 13-year period. Barksdale and others, 1958, showed by flow pattern analyses in Figure 18 that the artesian pressure in the Potomac artesian aquifer was above 20 feet in all of Delaware north of the Chesapeake and Delaware Canal where the Potomac aquifers occur. Likewise, William Back, 1966, of the U. S. Geological Survey showed by a hydrochemical flow pattern model that the artesian pressure was adequate (65 to 20 feet) to protect the fresh water in the Potomac to a depth of more than 1,000 feet before pumping began (Figure 19).

Sundstrom and others, 1967, found from their study of the Chesapeake and Delaware Canal area that the artesian pressure before heavy pumping began was 20 feet or more above sea level in both the Lower and Upper Potomac aquifer in the eastern part of the Canal area. All evidence indicates that the artesian pressure in the Lower Potomac aquifer in the Midvale-Llangollen Estates area

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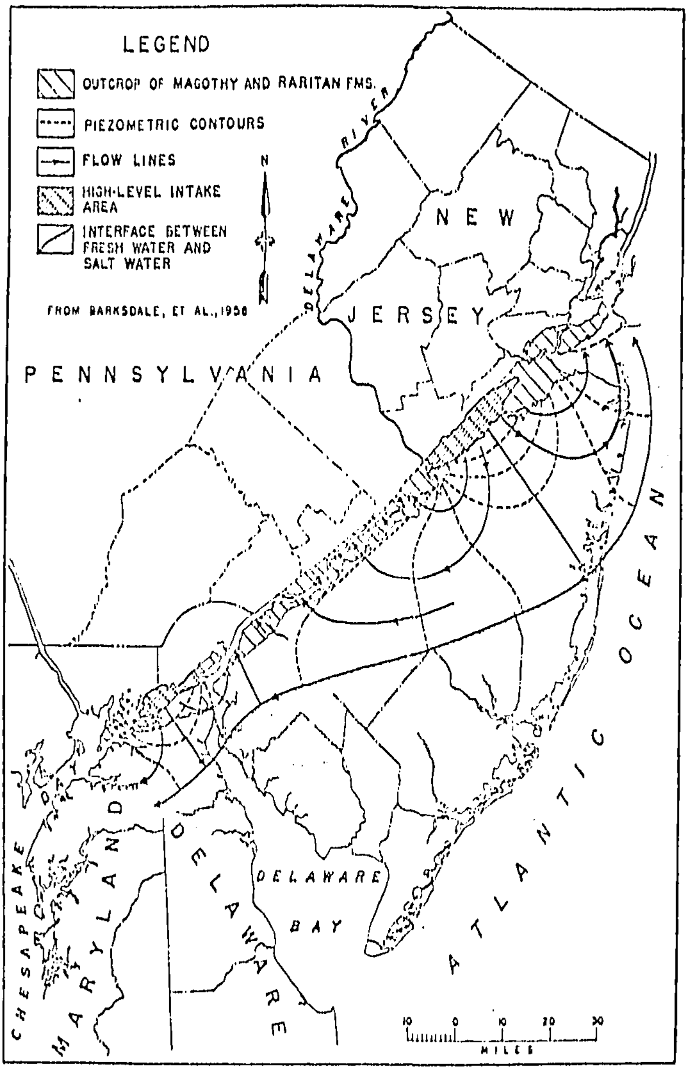

Figure 18 MAP SHOWING LOCATION OF FLOW PATTERNS AND FRESH WATER-SALT WATER INTERFACE

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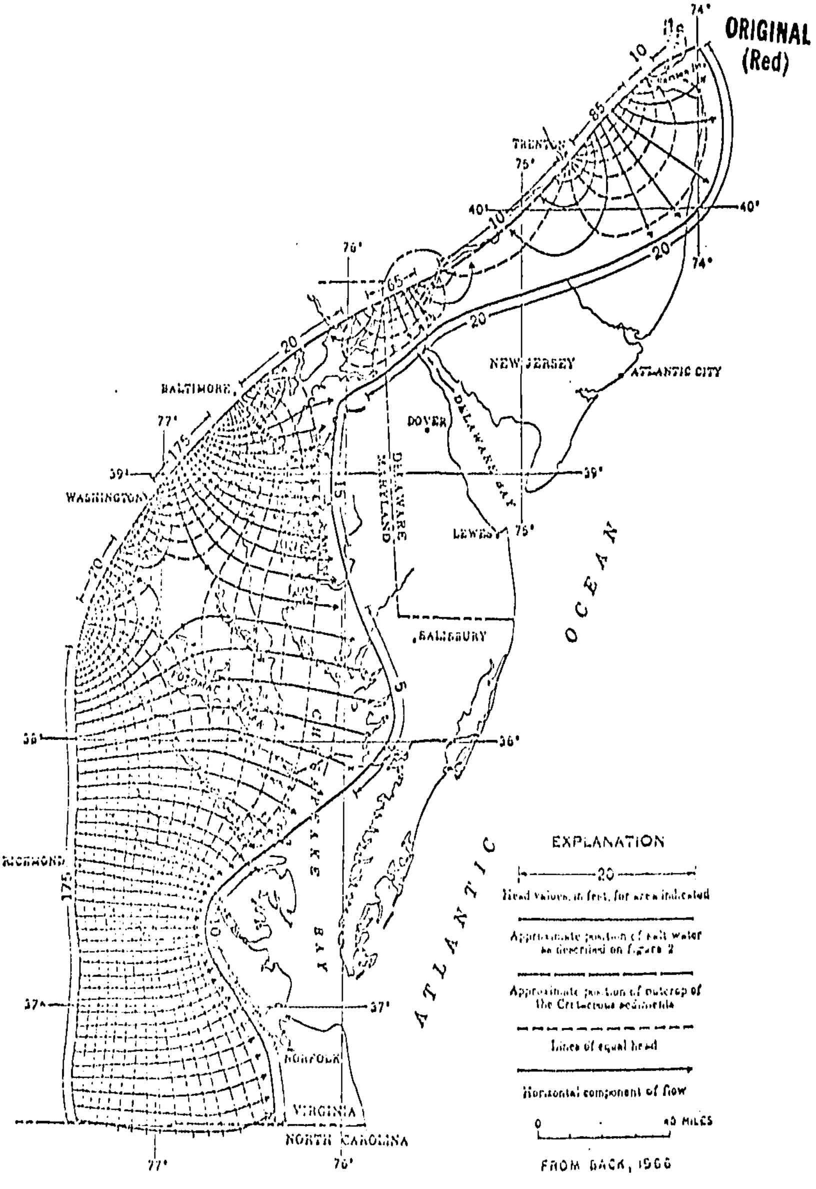

FIGURE 19. GENERAL PATTERN OF GROUND-WATER ... THE CRETACEOUS SEDIMENTS.

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prior to the development of the aquifer at the Delaware Rayon Company Plant in 1915 was 20 or more feet above sea level.

Much more information is available about the water levels and artesian pressures in the Upper Potomac aquifer before heavy pumping began. Table 7 lists measurements of water levels in 18 wells in the Upper Potomac aquifer in the Midvale-Llangollen Estates and surrounding area. The measurements were made from 1942 to 1961. The two wells measured in 1961 are influenced by pumping in the Midvale-Llangollen Estates area. When the first well was drilled in 1952 at the Artesian Water Company Llangollen Estates well field, the artesian pressure in Kelly well #1 was 28 feet above sea level. When Kelly well #3 was dug six years later in 1958 the static artesian pressure was 13 feet above sea level, indicating a decline of 15 feet in six years. Table 7 shows the highest observed artesian pressure 56 feet above sea level. Figure 19 by Back, 1966, shows from the flow net pattern in the Delaware area that the artesian pressure ranges from 65 to 20 feet above sea level.

In the water-table aquifer of the Pleistocene and subcropping Upper Potomac sands the water levels were observed by the U. S. Geological Survey and the Delaware Geological Survey. In 1964, the U. S. Geological Survey published Hydrologic Atlas 79 which gives the altitude of the water table. That portion of the Atlas that includes the Midvale-Llangollen Estates area is included herein as Figure 20. A recent study of the water-table aquifer at Llangollen Green in the vicinity of the Artesian Water Company well field made by E. H. Richardson Associates shows that there has been no major change in the altitude of the water table in the shallow aquifer since the water-level measurements for Hydrologic Atlas 79 were made by the U. S. Geological Survey in September 1958. Most of the changes in the water table have occurred (1) in the areas

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Table 7

Water Level Altitudes in Wells in the Upper Potomac
Ground-Water Reservoir in the Midvale Llangollen Estates and Surrounding Area
Prior to the Heavy Withdrawal of Ground Water from the Aquifer in the Area

Well	Owner	Depth in Feet	Altitude of Water Level (MSL)	Date Measured	Source of Data
Cd 41-18	Delaware State Hospital	80	+43	3-18-61	Sundstrom & Pickett, 1971
Cd 42-13	--	73	+19	11-53	do
Cd 52-13	City of New Castle	132	+ 5	8-20-52	do
Cd 52-15	Artesian Water Co. (Castle Hill)	73	+19	11-53	do
Db 15-1	T. Dianich	136	+27	1951	do
Db 35-3	Artesian Water Co.	120	+56	1955	do
Db 35-4	do	100	+55	11-2-53	do
Dc 12-4	B.G. Head	57	+30	7-53	do
Dc 22-8	R. Dasher	91	+54	5-16-55	do
Dc 24-1	Artesian Water Co. Kelley #1	168	+28	5-23-52	Files Delaware Geol. Survey
Dc 23-9	Artesian Water Co. Kelley #3	163	+13	8-58	do
Dc 22-1	S. Medwick	96	+36	9-11-46	do
Dc 22-2	do	85	+40	9-18-46	do
Dc 22-3	do	85	+37.5	9-18-46	do
Dc 22	Liddell	119	+33.5	9-42	DGS Bull. 4, 1955
Dc 23	Dr. H.A. Carl	99	+43.5	1942	do
PW-2	Amoco Chemical	166	- 0.8	4-17-61	Leggette, Brashears and Graham Report to Avisun Corp.
PW-3	Amoco Chemical	146	+ 2.6	5-31-61	do

Note: The static water level in the area of PW-2 and PW-3 has been lowered, presumably by prior pumping of wells at the Avisun Corporation old plant, at the Artesian Water Company Llangollen Estates Well Field, and other wells in the area.

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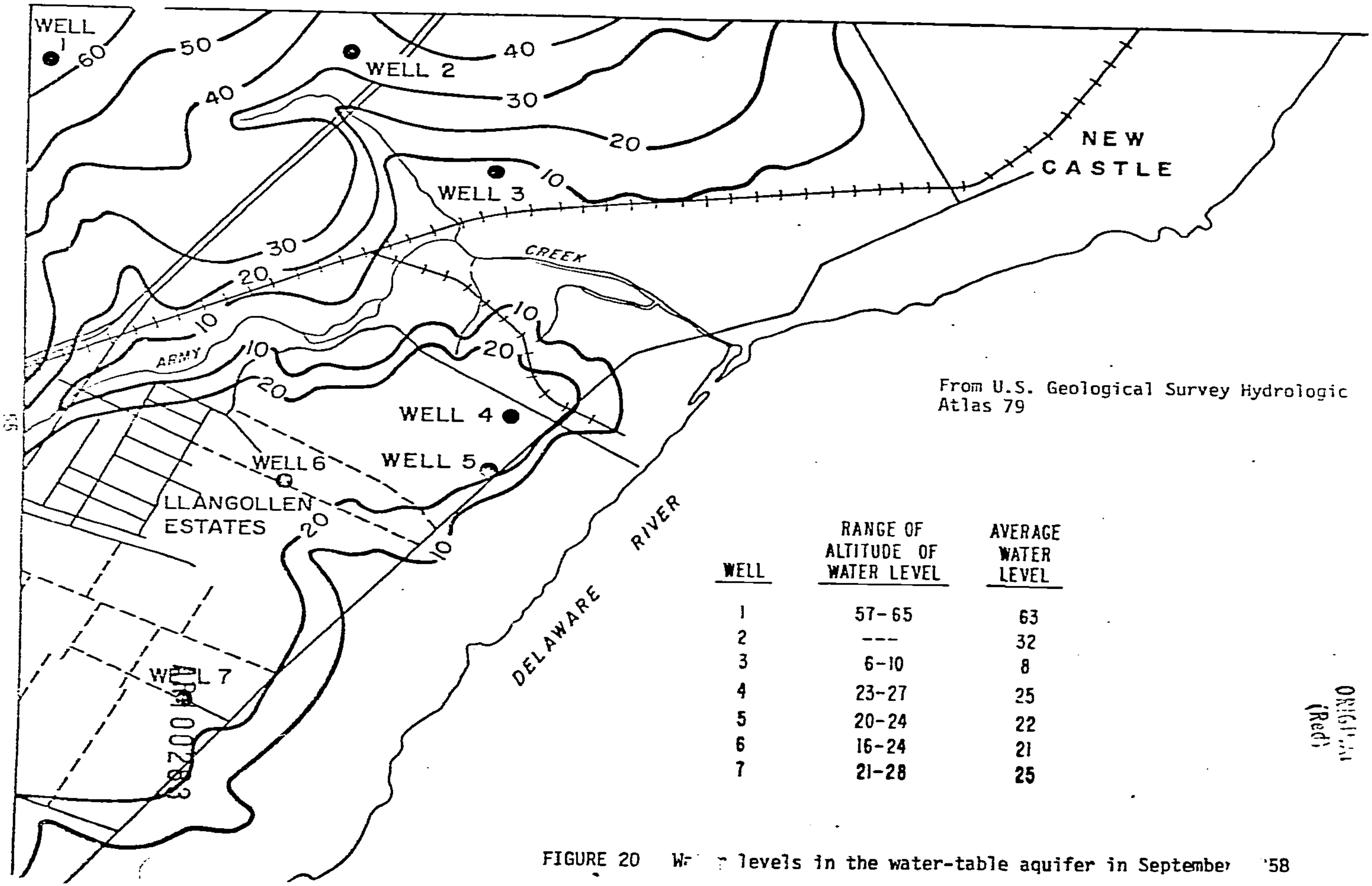

From U.S. Geological Survey Hydrologic Atlas 79

WELL	RANGE OF ALTITUDE OF WATER LEVEL	AVERAGE WATER LEVEL
1	57-65	63
2	---	32
3	6-10	8
4	23-27	25
5	20-24	22
6	16-24	21
7	21-28	25

FIGURE 20 W[illegible] levels in the water-table aquifer in Septembe[illegible] '58

where sand and gravel have been removed in gravel pits that penetrate the water table and (2) in the outcrop-subcrop area supplying recharge to the Upper Potomac aquifer in the Midvale-Llangollen Estates area.

Pumpage and the Decline in Water Levels

Pumpage has increased in the Lower Potomac aquifer by about 400 gallons a minute in a 12-year period from 1961 to 1973. The increase took place in the new Amoco Polymer Plant which put well PW-1 into service in 1961. According to extensive pumping tests made on well PW-1 by Leggette, Brashears and Graham, the transmissive properties are very low at the well, only 2,000 gallons a minute per foot. Leggette, Brashears and Graham conclude from their study that the well will produce 400 gallons a minute (576,000 gallons a day) continuously and can produce up to 500 gallons a minute for several weeks if the need for the water should arise. The consultants also conclude that because of the poor transmissive properties of the aquifer, the 250-acre tract in which the well is located will only support the one well. In 1973 a well on the Reni property near the Llangollen landfill was drilled to a depth of 554 feet with a very poor showing in the Lower Potomac aquifer. Well PW-1 at the Amoco Polymer Plant required more than 120 feet of drawdown to produce only 400 gallons a minute in 1961.

Pumpage has increased more than seven fold from the Upper Potomac aquifer in the 20-year period from 1952 through 1972. In 1952 according to Marine and Rasmussen, 1955, the Delaware Rayon Plant (later Amoco Film Plant and now Crown-Zellerbach) shut down all operations and reworked the plant to require about one half the water previously used. The reduced rate averaged 630,000 gallons a day. This rate coupled with the other uses from the Upper Potomac in the

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Midvale-Llangollen Estates area brought the estimated total use to a million gallons a day or less. A part of the water pumped at the Delaware Rayon Plant was obtained from the Lower Potomac aquifer from wells completed in both the Upper and Lower Potomac aquifers. By comparing the transmissive properties of the two aquifers, it is estimated that most of the water pumped came from the upper aquifer.

According to records of the Delaware Geological Survey, Artesian Water Company started their Llangollen Estates well field in May 1952 when they completed their first well known as Kelly #1. According to the records the static water level in the well was 32 feet below land surface. Land surface has since been determined to be 60 feet above sea level, giving the original static water level an altitude of 28 feet above sea level. The well was reported to yield 670 gallons a minute. Since 1952 the Artesian Water Company has expanded the Llangollen Estates well field to include seven Kelly type dug wells and five steel cased and screened wells. The pumpage from the wells as shown in Table 3 has grown to an average of 3,500,000 gallons a day with a peak demand of 5,200,000 gallons a day in 1972.

The decline in water levels in Artesian Water Company's Llangollen Estates well field has been substantial. The static water level of 28 feet above sea level when Kelly #1 was dug was probably representative of the field as a whole. In September 1973 all production in the well field and at Amoco Polymer Plant Upper Potomac wells was stopped so that Roy F. Weston personnel could make water-level observations in the Llangollen landfill area for the Department of Public Works in New Castle County. On September 9, 1973, after three or four days of shut down of the well fields, Michael Apgar of Roy F. Weston, Inc. measured the static water levels in four wells of the Artesian Water Company in

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the Llangollen Estates well field as follows: Artesian Water Company Well 6, static water level 22.58 feet below sea level; Artesian Water Company Well 7, static water level 36.94 feet below sea level; Artesian Water Company Well 2, static water level 26.88 feet below sea level; and Artesian Water Company Well G-3, static water level 17.60 feet below sea level. The foregoing measurements indicate that the static water level has declined from 46 to 65 feet in the well field since the first well started pumping in 1952.

Pumpage from the Upper Potomac aquifer at the Amoco Polymer Plant began in 1961 when wells PW-2 and PW-3 were put into service. Well PW-2 has produced on test 1,000 gallons a minute and PW-3 has been tested at 800 gallons a minute. From the tests Leggette, Brashears and Graham state that the two wells are capable of producing 2,000,000 gallons a day. One of the two wells is usually used in conjunction with well PW-1 which draws water from the Lower Potomac aquifer at a rate of 400 gallons a minute.

The static water level in Amoco Polymer Plant well PW-2 was eight tenths foot below sea level when the well was completed April 17, 1961. The static water level in Amoco Polymer Plant well PW-3 was two and six tenths feet above sea level when the well was completed May 31, 1961. It is interesting to note that if the static water level was the same in 1952 as that of Artesian Water Company Kelly Well #1 of 28 feet above sea level, the decline in static water level at PW-2 and PW-3 had amounted to 28.8 and 25.4 feet respectively when the two wells were completed in 1961 and since pumpage started in the Llangollen Estates well field by Artesian Water Company in May 1952.

Table 8 gives the water levels in test wells to the Upper Potomac aquifer as measured by the Delaware Geological Survey on November 27, 1972, in the Llangollen landfill area. Figure 21 shows the location of the test wells.

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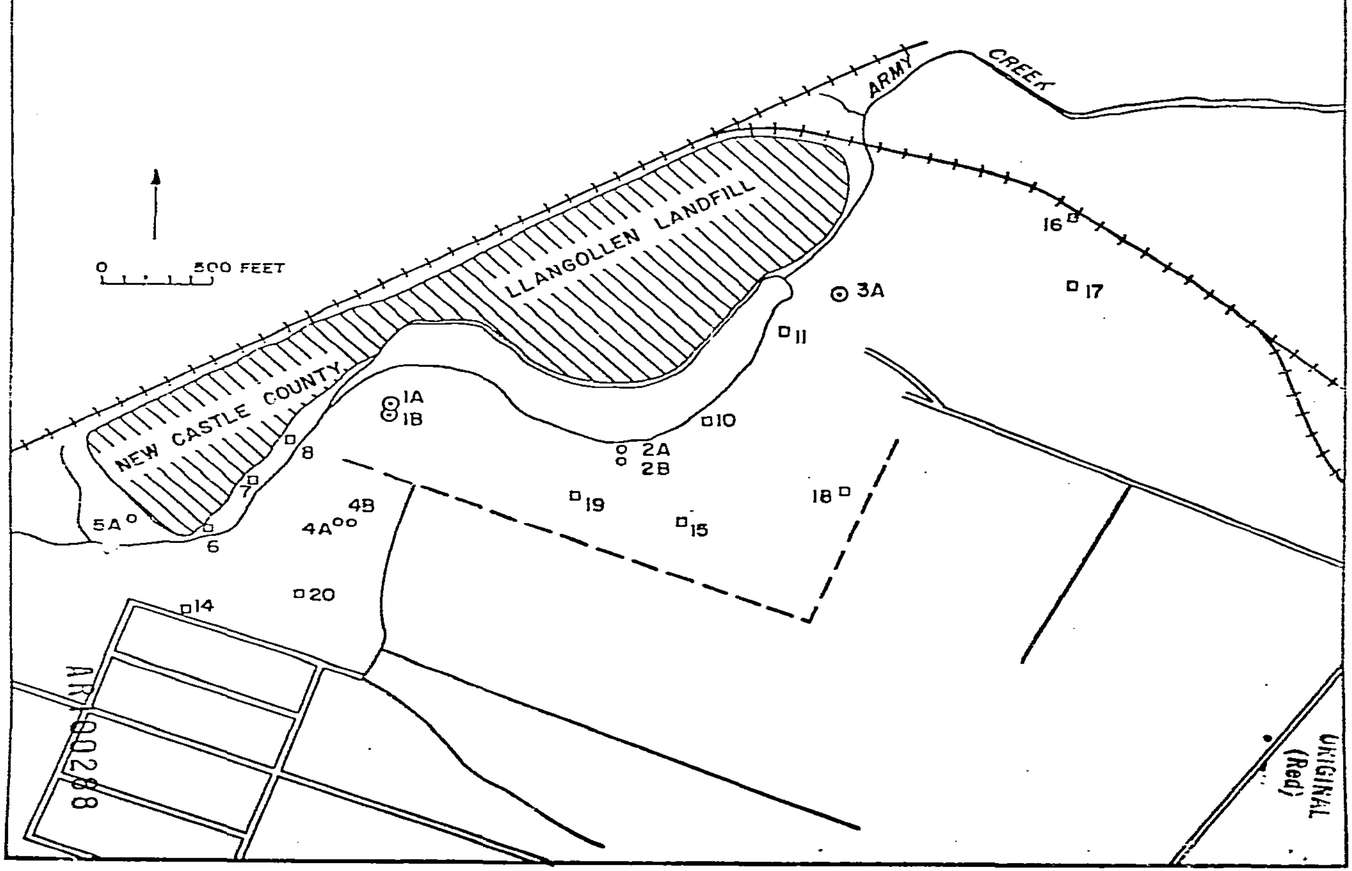
Table 8

Water Levels in the Upper Potomac Aquifer
in the Llangollen Landfill Area, November 27, 1972.

Well	Altitude of Water Level in Feet	Well	Altitude of Water Level in Feet
1A	-15.45	8	-21.35
1B	-15.64	10	-16.97
2A	-18.44	11	-11.83
2B	-17.76	14	-14.39
3A	-13.10	15	-20.01
4A	-16.27	16	-13.64
4B	-16.36	17	-23.55
5A	-11.46	18	-24.97
6	-14.26	19	-19.18
7	-10.01	20	-18.24

* Measurements made by the Delaware Geological Survey

FIGURE 21 Llangollen landfill test wells listed in Table 8



Available Drawdown to the Bottom of the Confining Clay in Wells in the Upper Potomac Aquifer

The available drawdown in wells in the Upper Potomac aquifer to the bottom of the dense confining clay in the Artesian Water Company well field ranges from about 40 to 73 feet below sea level. The bottom of the clay at Amoco Polymer Plant wells PW-2 and PW-3 is 63 and 70 feet below mean sea level. When the artesian pressure is lowered below the confining clay, the aquifer at that point ceases to be artesian and changes to water-table conditions. As this transition takes place the coefficient of storage changes from the very low figure of about 0.0005 and starts to approach the water-table figure of about 0.15. Thus, as the aquifer becomes water table in character, much of the water is obtained locally from storage and the shape of the cone of depression changes drastically. The result of this change is a decrease in the saturated thickness of the aquifer and, therefore, a decrease in transmissivity, causing an accelerated decline in the pumping level in the well and a decline in the yield of the well.

In all of the wells with steel casing and screen in the Artesian Water Company Llangollen Estates well field and in the Amoco Polymer Plant well field the screens are set several feet below the bottom of the confining clay. In these wells the tops of the screens become the limit of drawdown, although a part of the aquifer is being unwatered at the wells before reaching the top of the screens. Table 9 gives the approximate altitude of the surface as the well, the approximate depth below sea level of the bottom of the confining clay, depth below sea level of the top of the screen and pumping levels measured below sea level in September 1972. The pumping levels were measured by Michael Apgar of Roy F. Weston, Inc. for New Castle County.

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Table 9

Altitude of Land Surface, Depth to Base of Confining Clay, Depth to Top of Screen in Well and Pumping Level Below Sea Level in Wells, September 1972

Well	Owner	Altitude of Land Surface in Feet	Depth Below Sea Level of Bottom of Clay in Feet	Depth Below Sea Level of Top of Screen in Feet	Pumping Level Below Sea Level in Feet
E-1	Artesian Water Co.	39	48	83	--
E-2	do	33	54	98	77
G-3	do	20	54	95	62
J-1	do	11	73	111	--
K-1	do	29	73	106	82
PW-2	Amoco Polymer Plant	25	63	101	73
PW-3	do	22	70	95	83

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The Available Drawdown to the Top of the Screens in Wells in the Upper Potomac Aquifer

The pumping levels shown in Table 9 were made while Artesian Water Company wells E-2, G-3, K-1, Kelly #2 and 7 were all pumping at a combined rate of 4,800,000 gallons a day. Wells PW-2 and PW-3 of the Amoco Polymer Plant well field were pumping at a rate of 1,800,000 gallons a day which is the capacity of the two wells in that field. The Artesian Water Company had other wells in their field that could have been used to increase the pumpage from their well field on a short-term basis. According to the recorded pumping levels in Table 9, all of the five pumped wells had pumping levels below the bottom of the confining clay. The range was eight to 23 feet below the bottom of the clay and the average was 13 feet. The pumping levels ranged from 12 to 33 feet above the top of the screen in the pumped wells. In 1972 Artesian Water Company had short peak periods of pumping from the Llangollen Estates well field at rates of 5,200,000 gallons a day. When applying these rates of pumpage to the results shown in Table 9, it is evident that the Amoco Polymer Plant well field and the Artesian Water Company Llangollen Estates well field have reached their ultimate development for available water. Sustained pumping at the Llangollen Estates well field at a rate of 5,200,000 gallons a day will probably drop the pumping levels below the top of the well screens and result in decreased yield and probable damage to both the wells and the aquifer.

The Availability of Recharge

The availability of recharge to the Potomac Formation has been estimated by Barksdale and others, 1958, to be about 21 inches of the available rainfall annually to the Lower Potomac aquifer in Delaware on the outcrop and subcrop of the aquifer. The outcrop-subcrop of the Lower Potomac aquifer is extensive to the north and west of the Midvale-Llangollen area and is far more than adequate to supply the small amount of water pumped from the Lower Potomac aquifer at the Amoco Polymer and Film Plants. The low transmissive properties of the Lower Potomac aquifer preclude further development of it in the area. The effect of pumping on the aquifer by wells in the Getty well field are probably offset by the positive effect of recharge which is within comparable distance with the Getty wells.

The availability of recharge to the Upper Potomac aquifer in the Midvale-Llangollen Estates area is much more difficult to appraise because of the lack of definite knowledge of the position of the subcrop beneath the Pleistocene and to the effects of discontinuity from erosion of the confining clay by action of ancestral drainage of Army Creek or other drainage in the area. Clues to the areas of deposition of the subcrop of the Upper Potomac are suggested by examining the map of the thickness of the Potomac Formation and relating the position of the sand of the Upper Potomac to their extended position on the thickness map, making allowance for the general dip of the Upper Potomac of 40 to 45 feet to the mile. Such an analysis suggests that the subcrop may comprise eight to 12 square miles lying in an irregular arc of about 180 degrees counterclockwise northeast to southwest. The effective subcrop probably would range from one to three miles in width. A smaller amount of subcrop (perhaps one to two square miles) may be provided by the absence of the confining bed in the ancestral drainage of Army Creek or other areas where the clay is absent. The severe declines in artesian head in the Llangollen area during the pumping from the Amoco and Artesian Water Company well fields at a combined rate of about 5,500,000 gallons a day in 1972 provides some evidence that the effective recharge area may be less than eight to 12 square miles.

Marine and Rasmussen, 1955, prepared a cross section at Delaware Memorial Bridge (Figure 17) on which they plotted a geologic section from the test borings for the bridge. They show that the bed of the Delaware River reached a depth of about 105 feet below sea level and has filled to 45 feet below sea level at its deepest place during Pleistocene and Holocene time. When the Delaware River was at its lower stages, drainage to it must have removed much Potomac Formation material as the streams flowed to the river. Evidence of this is found in the logs of test wells 10, 11 and 15 near Army Creek in the Llangollen landfill area, in which the Delaware Geological Survey found the confining clay absent. At Midvale a log of an Artesian Water Company well published by the Delaware Geological Survey, Bulletin 4, shows the Pleistocene in direct contact with sands of the Upper Potomac.

Based on the above evidence and the fact that the sand sections blend into clayey sections, it appears that the well fields in the Upper Potomac aquifer when pumping to capacity may be approaching or exceeding the limits of recharge supply.

The Effect of Recharge on Pumping Levels in the Upper Potomac Aquifer

The effect of recharge on pumping levels in the artesian part of the Upper Potomac aquifer in the Midvale-Llangollen Estates area is substantial because of the proximity to the recharge area, so long as artesian conditions are maintained in the aquifer and the artesian aquifer is functioning primarily as a conduit from the recharge area to the wells. In places where overpumping is

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taking place, the water levels are being lowered below the confining clays and the aquifer is changing from artesian to water-table conditions. When such a change takes place the water pumped from a well is obtained largely from local storage in the aquifer, and the water levels in the aquifer and the yield of the wells decline rapidly. Such a condition can be expected if the large wells in the Amoco well field, in the Artesian Water Company Llangollen Estates well field and the Llangollen landfill retrieval wells are pumped at combined rates that overtax the Upper Potomac aquifer locally. Careful coordinated management of pumping, based on water level, pumping level and pumping rate observations, must be made throughout the entire Midvale-Llangollen Estates area. This management is especially necessary until the leachate contaminants from the landfill are removed from the aquifer and should be continued later in maintaining the safe yield of the aquifer. The foregoing data presented on rates of pumping, decline in water levels, available recharge and other aquifer characteristics strongly suggest that at the upper rates of pumping in the Midvale-Llangollen Estates area, the available recharge to the Upper Potomac aquifer may have been reached or possibly exceeded.

Limit of Development of the Lower Potomac Aquifer in the Midvale-Llangollen Estates Area

The limit of development in the Lower Potomac aquifer has been reached in the Midvale-Llangollen area by the wells to the aquifer now in use at the Amoco Film Plant and at the Amoco Polymer Plant. An extensive study of the Polymer Plant well data and pumping test by Leggette, Brashears and Graham, 1961, reveals that the well will produce 400 gallons a minute (576,000 gallons a day) continuously and could produce up to 500 gallons a minute for several

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weeks if the need should arise. The consultants also concluded that because of the very poor transmissive properties of the aquifer as demonstrated by the pumping test, the 250-acre tract in which the well is located will only support the one well. The Lower Potomac aquifer was examined in a test well drilled on the Reni property just south of the Llangollen landfill. No promising sources of water were found in the Lower Potomac aquifer in this test well to a depth of 554 feet below land surface. Very little, if any, additional water can be assured by drilling more wells to the Lower Potomac aquifer in the Midvale-Llangollen Estates area.

Limit of Development of the Upper Potomac Aquifer in the Midvale-Llangollen Estates Area

The limit of development of the Upper Potomac aquifer in the Midvale-Llangollen Estates area, based on the rate of decline in artesian pressure cause by pumping the wells, the available drawdown to the bottom of the confining clay and the top of the screens, the estimated available recharge area and the transmissive and storage properties of the aquifer, appears to be not more than an average of about 6,500,000 gallons a day and may prove to be less. The developed capacities of wells to the Upper Potomac artesian aquifer in the Midvale-Llangollen Estates area by Amoco, Artesian Water Company, New Castle County and others far exceed the capacity of the aquifer to deliver water under artesian conditions on a long-term basis. The Amoco Chemical Company has established use from the aquifer of about 2,000,000 gallons a day. The Artesian Water Company uses an average of about 3,500,000 gallons a day with summer peaks reaching 5,200,000 gallons a day. New Castle County has recently put into operation several wells for the purpose of retrieving leachate contaminated water in the aquifer from the Llangollen landfill. The County retrieval wells are designed to remove 3,000,000 to 4,000,000 gallons a day. During the period of pumping to remove the water contaminated by leachate, it appears certain that a part of the normal pumping from the Upper Potomac aquifer in the Midvale-Llangollen area must be curtailed.

Development of the Pleistocene Water-Table Aquifer in the Midvale-Llangollen Estates Area

The development of ground water from the Pleistocene water-table aquifer has not been large in the Midvale-Llangollen Estates area because the saturated thickness of the Pleistocene is not thick enough to provide adequate drawdown in the aquifer to sustain the pumpage from large capacity wells. In the northern and northwestern part of the area where the Pleistocene is in direct contact with the subcrop of the Upper Potomac aquifer, wells of more than 300 gallons a minute have been developed under water-table conditions. Drillers' logs and water-level data indicate, however, that most if not all of the water is being obtained from the subcropping water-table aquifer of the Upper Potomac.

The Pleistocene water-table aquifer does have much importance in collecting precipitation for recharge to the Upper Potomac aquifer supplying the area and in providing fair weather discharge to Army Creek and to the wetlands of the Delaware estuary.

PROBLEMS OF AQUIFER CONTAMINATION

Since the spring of 1972 contamination on the Upper Potomac artesian aquifer, the Pleistocene water-table aquifer and Army Creek has been observed in parts of the Midvale-Llangollen Estates area. The contamination is found in Army Creek, the Upper Potomac and Pleistocene aquifers south and southeast of the Llangollen landfill. The Llangollen landfill was started in 1960 and completed in 1968 by New Castle County. In 1960 when the landfill was started, pumpage was light in the area because the Amoco Polymer well field had not been developed and the Artesian Water Company Llangollen Estates well field had been developed less than eight years, and the total pumpage from it probably averaged considerably less than 1,000,000 gallons a day. In 1960 when the landfill was started the water levels in the Upper Potomac and the Pleistocene were largely in hydrologic equilibrium and largely in conformity to those in the Pleistocene water-table aquifer as observed by the U. S. Geological Survey and Delaware Geological Survey between 1950 and 1963. The altitude of the water table has been mapped and published by the U. S. Geological Survey as Hydrologic Atlas 79. Figure 20 shows the altitudes of the water table in the Midvale-Llangollen Estates area as shown on Atlas HA-79. A careful study of the water level altitudes shows that the discharge from the Pleistocene and subcrops of the Potomac in the area was toward Army Creek and the wetlands of the Delaware estuary.

In 1972 water levels in the Pleistocene water-table aquifer continued above sea level except in areas near the Llangollen landfill where the confining clay above the Upper Potomac aquifer was absent and the ground- AR100297 drainage pattern from the water-table aquifer was still to Army Creek and the wetlands of the Delaware estuary. However, the water-table aquifer of the Pleistocene and the discharge from Army Creek were losing a part of their water to the subcrop of the Upper Potomac aquifer in 1972. In the vicinity of the Llangollen landfill, static water level measured in 20 test wells in the Upper Potomac aquifer November 27, 1972, by the Delaware Geological Survey ranged from 10.01 feet to 24.97 feet below sea level (see Table 8 and Figure 21). Pumping levels at the Artesian Water Company Llangollen Estates well field were measured by Michael Apgar of Roy F. Weston, Inc. in three wells (K-1, E-2, G-3) and found to range from 62 to 82 feet below sea level in September 1972. Pumping levels in wells P-2 and P-3 at Amoco Polymer well field were measured at 73 and 83 feet below sea level. Figure 22 gives the theoretical ground-water flow pattern as mapped by Mr. Apgar from the September 1972 observations. The above observations of the changes in water levels and the flow pattern are relative to the problems of contamination that now exist. A hydraulic gradient at times of 90 feet to the mile has been established between the Llangollen landfill and the two well fields by the pumping that has been taking place in them. Thus, a substantial portion of the contaminated ground water discharging from the landfill to the Pleistocene aquifer is finding its way to both Army Creek and subcrops of the Upper Potomac where it is drawn by the steep hydraulic gradient from the landfill and Army Creek toward the well fields.

Area and Extent of Aquifer Contamination

Twenty eight well logs (located on Figure 23) in and around the contaminated area of the Llangollen landfill were examined to ascertain (1) the thickness of the Pleistocene and younger sands covering the surface of the area;

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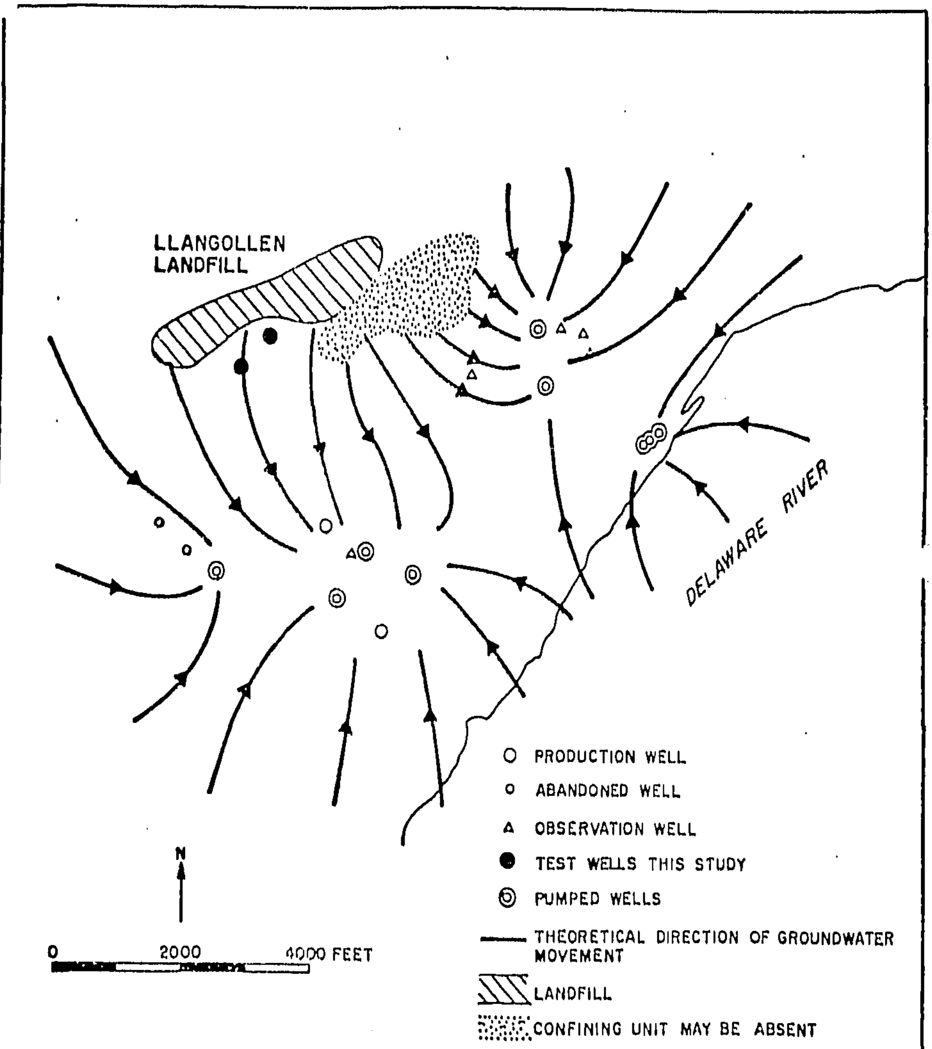
FIGURE 22 Map showing theoretical flow pattern in the Upper Potomac aquifer, September 1972



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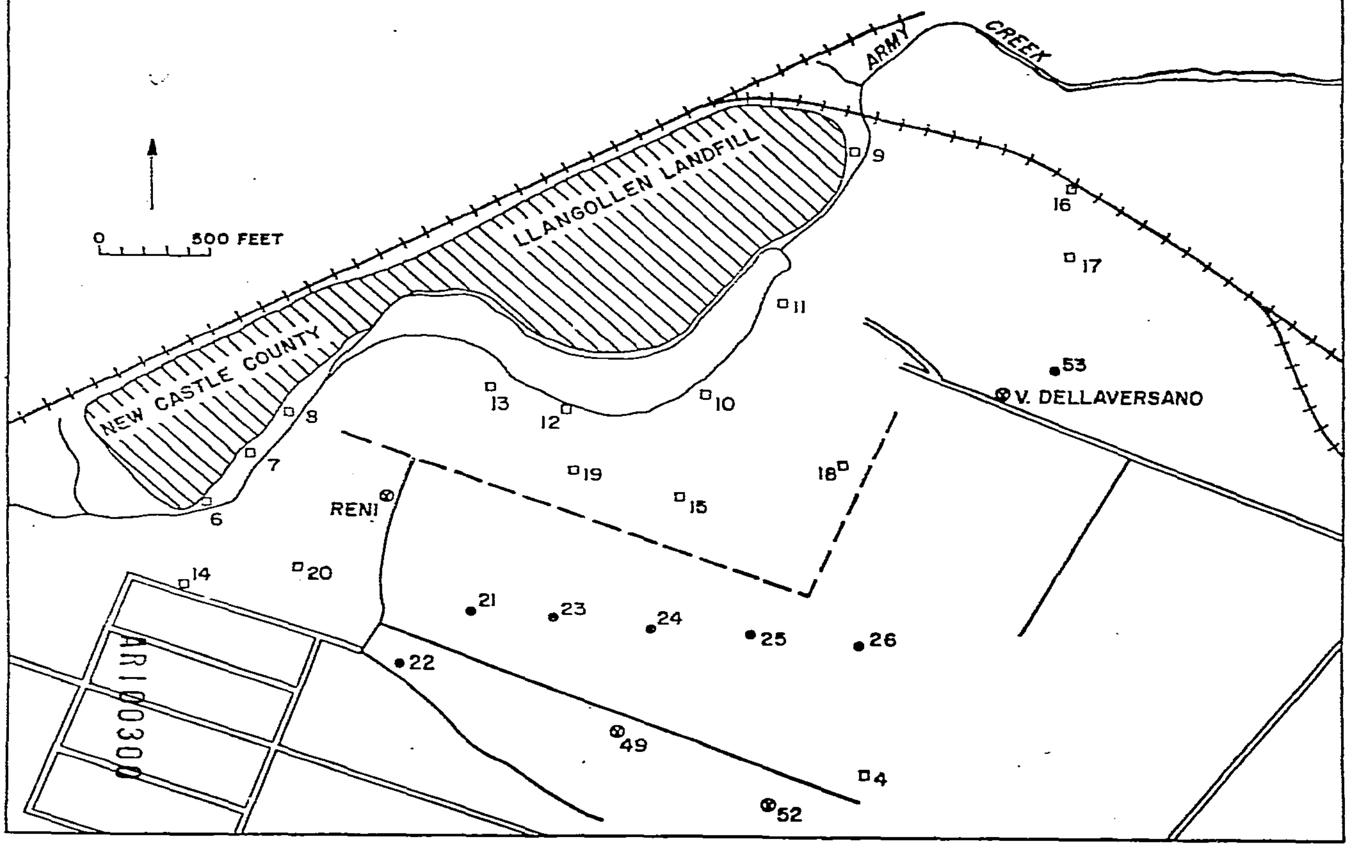
MODIFIED FROM: MICHAEL APGAR, 1972

FIGURE 23 Llangollen landfill test and private wel.. listed in Table 11



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(2) the thickness of the confining clay between the Pleistocene and Upper Potomac aquifer; and (3) the thickness of the Upper Potomac aquifer beneath the confining bed. Table 10 summarizes the analyses of the 28 well logs. The logging of wells numbered 5 through 20 was done by Mr. Kenneth D. Woodruff and Mr. John C. Miller of the Delaware Geological Survey. The logs of wells 21 through 53 were furnished by Mr. Michael Apgar of Roy F. Weston, Inc. Drillers' logs of the remaining private wells were obtained from the Delaware Geological Survey and Mr. Apgar.

The contaminated area and the area in which water must be diverted toward recovery wells to remove the contaminants is estimated to extend about 5,600 feet in length and averages about 2,400 feet in width as of January 1, 1974. This area includes the landfill as well as the contaminated area downdip from the landfill and some intermingled uncontaminated areas that must be included in pumping for contaminant retrieval. The area comprises about 13,500,000 square feet or about 310 acres. The average thickness of the aquifer is 68 feet, indicating that about 21,000 acre feet of saturated material are in the area where the contaminants must be removed. The effective specific yield of the aquifer has not been determined, but probably ranges between 11 and 17 percent of the volume of the aquifer. If the effective specific yield is 11 percent, the 21,000 acre feet of saturated material in the contaminated area would contain about 2,300 acre feet of contaminated water. If the effective specific yield is 17 percent, the contaminated water would amount to about 3,600 acre feet. For this study a specific yield of 14 percent is the estimated median and has been used for the estimates that follow. Using 14 percent as the specific yield, the volume of water that must be removed from the contaminated area amounts to about 3,000 acre feet of water.

Table 10

Llangollen Landfill Area Wells Showing the Position of
Pleistocene Sand and Gravel, Potomac Confining Clay, and Upper Potomac Aquifer

Well	Pleistocene		Confining Clay			Upper Potomac Aquifer			
	From (Feet)	To (Feet)	From (Feet)	To (Feet)	Thickness (Feet)	From (Feet)	To (Feet)	Thickness (Feet)	
5	0	26	26	124	98	No acceptable aquifer encountered--John C. Miller			
Ren 1 New Dc14-15B	1	57	57	85	28	85	159	74	
6	Cannot interpret								
7	0	11	11	39	28	39	111	72	
8	0	6.5	6.5	78	72	78	98	20	
9	0	36	53	71	18	71	113	42	
10	0	25	Absent			25	107	82	
11	0	16	Absent			16	96	96	some thin clay streak
12	0	17	17	75.5	59	76	111	35	
13	0	11	11	74	63	74	112	38	
14	0	38	38	84	46	84	131	47	
15	0	21	Absent			21	131	110	
16	0	27	27	42	15	42	140	98	
17	0	12	12	73	61	73	142	69	
18	0	4	4	54	50	54	131	77	
19	0	30	30	47	17	47	141	94	
20	0	45	45	96	51	96	138	42	
21	0	45	45	79	34	79	169	90	
22	0	50	50	71	21	71	159	88	
23-B	0	41	41	69	28	78	170	92	
24	0	51	51	78	27	78	167	89	
25	0	39	39	79	40	79	166	87	
26	0	23	23	83	60	83	168	85	
49	0	56	56	89	33	89	157	68	
52	0	6	6	84	78	84	163	79	
53	0	5	5	70	65	70	93	23	
V. Dell Aversano	0	25	25	84	59	84	135		
J. [illegible]racher	0	15	15	100	85	100	145	45	

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Experiences, elsewhere, at El Paso (Sundstrom and Hood, 1952) and Amarillo (Moulder and Frazor, 1957), Texas, have shown that contaminated aquifers were relieved of about 95 percent of the injected contaminant after pumping about three times the volume of contaminated water injected. This would indicate that perhaps as much as 9,000 acre feet of water must be pumped from properly located retrieval wells to remove most of the presently contaminated water. The removal of 9,000 acre feet of water at a continuous rate of pumping of 3,000,000 gallons a day would require about two and a half years of pumping, assuming no additional input of contaminant from the landfill. An acre foot is 43,560 cubic feet of water or 325,839 gallons.

QUALITY OF GROUND WATER IN THE MIDVALE-LLANGOLLEN ESTATES AREA

The quality of the ground water and the water of Army Creek has received much attention since leachate contamination from the Llangollen landfill was discovered in the ground waters of the Pleistocene and Upper Potomac and the surface water of Army Creek in the vicinity of the Llangollen landfill. The concentration and extent of contamination have been given a large amount of analyses and study by Roy F. Weston, Inc., consultants for New Castle County, and by the Delaware Department of Natural Resources and Environmental Control. Two detailed reports have been prepared by Roy F. Weston, Inc. in 1972 and 1974 for New Castle County and are available for reference in the New Castle County Department of Public Works. The Department of Natural Resources and Environmental Control has conducted a large analytical program of testing the contaminants in wells to the Upper Potomac formation in the vicinity of the Llangollen landfill. Monthly results of these analyses are in the files of the Department of Natural Resources and Environmental Control and in the files of the New Castle County Department of Public Works. The analyses and study need to continue for some time in the future before a complete appraisal of the contamination problem and remedial measures now under way can be made.

The quality of water from well PW-1 in the Lower Potomac aquifer and from wells PW-2 and PW-3 in the Upper Potomac aquifer in the Amoco Polymer Plant well field when the wells were drilled in 1960 and 1961 is given in Table 11.

The chloride content of the water in the Potomac aquifers close to the Delaware estuary was the concern of Sundstrom and others, 1967, when the Chesapeake and Delaware Canal area study of the Potomac aquifers was made.

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Table 11

Quality of Water in Wells of Amoco
Polymer Plant Well Field in 1960 and 1961

	PW-1	PW-2	PW-3
Date of Collection	10-25-60	4-18-61	6-1-61
Analyzed by	Thomas M. Riddick	Permutit Co.	Permutit Co.
Turbidity	20	5	3
Hardness ($CaCO_3$)	16	14	14
Carbon Dioxide, free (CO_2)	11	13	20
Iron (Fe)	0.2	0.1	0.1
Manganese (Mn)	0	-	-
Bicarbonate (HCO_3)	83	6	8
Nitrate (NO_3)	-	12	12
Chloride (Cl)	8	4	6
Color	5	3	3
Temperature (^{o}F)	58	55	55
pH	7.8	6.0	5.9

*Source of data: Leggette, Brashears and Graham, 1961.

Results are in parts per million, except for Color, Temperature and pH.

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Table 12 gives the results of chloride determinations made for the Canal study and 1974 chloride determinations for this study. The 1974 chloride determinations for the Upper Potomac wells PW-2 and PW-3 at the Amoco Polymer Plant well field show increases of chlorides of 27 parts per million for well PW-2 and 12 parts per million for well PW-3 from 1967 to 1974. Considering the leachate constituents in the samples, it is believed that the increase in chlorides comes from slight contamination of the aquifer by landfill leachate at wells PW-2 and PW-3.

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Table 12

Chloride Content of Water
from Potomac Formation Wells

Well	Date	Chloride in parts per million
Avisun Corp. Well PW-1	Oct. 25, 1960	8
	May 4, 1967	12
(Amoco)	June 4, 1974	10
Avisun Corp. Well PW-2	April 18, 1960	4
(Amoco)	May 4, 1967	9
	June 4, 1974	36
Avisun Corp. Well PW-3	June 1,1967	6
(Amoco)	May 4, 1967	9
	June 4, 1974	21
New Castle Water Co. Well 10	May 5, 1967	17
New Castle Water Co. Well (Dc51-8)	May 5, 1967	9
Tidewater Oil Co. Well P-3	Completion 1955*	10
(Eb15-4)	May 4, 1967	12
Tidewater Oil Co. Well P-4	Completion 1955*	19
(Dc51-7)	May 4, 1967	17
Tidewater Oil Co. Well P-5A	Completion 1955*	4.5
(Dc41-4)	May 4, 1967	8
Tidewater Oil Co. Well P-6A	Completion 1955*	10
(Dc42-6)	May 4, 1967	9
Tidewater Oil Co. Well P-9	Completion 1955*	8
(Ec12-20)	May 4, 1967	13
Tidewater Oil Co. Well P-10	Completion 1955*	22
(Ec14-7)	May 4, 1967	21
Tidewater Oil Co. Well P-16	Completion 1954	7
(Ec13-6)	May 4, 1967	9

*Source of data: Sundstrom and Others, 1967 and the Delaware Department of Natural Resources and Environmental Control, 1974.

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SURFACE WATER RESOURCES OF ARMY CREEK

The surface water resources of Army Creek in the Midvale-Llangollen Estates area are small in available quantity where water supply is concerned. The drainage area of the main stem of Army Creek above the marshlands and above its crossing by U.S. Highway 13 is about four square miles. The streamflow of Army Creek has not been recorded over a period of time. However, the U. S. Geological Survey has measured the daily discharge of nine streams in northern Delaware for periods ranging from 11 to 54 years. A summary of the streamflow is given in Table 13. The summary shows that the average discharge per square mile of drainage area ranges from one and fifteen hundredths to one and forty four hundredths cubic feet per second. The average discharge per square mile of drainage of the nine streams is one and twenty eight hundredths cubic feet per second. If the flow of Army Creek is equal to the average of the nine measured streams, the net fresh-water flow from the four square miles of drainage area is equal to an average of five and twelve hundredths cubic feet per second or 3,300,000 gallons a day. Based on the records of Shellpot Creek, Little Mill Creek and Blackbird Creek, the minimum daily discharge of Army Creek during periods of prolonged drought is probably close to zero. Storage would be required to use Army Creek water exclusively for water supply.

Army Creek is important to the Midvale-Llangollen Estates area in providing fresh-water drainage to the estuary and wetlands of the Delaware River.

Table 13

Summary of U. S. Geological Survey Streamflow Data for the Piedmont Plateau and Atlantic Coastal Plain Streams in Delaware

Stream	Location	Drainage Area (Sq. Miles)	Yrs. of Record 1/	Average Discharge (CFS) 2/	Maximum Discharge (CFS)	Minimum Discharge (CFS)	Average Discharge Per Square Mile (CFS)	Remarks
Piedmont Plateau Streams								
Shellpot Creek	Wilmington	7.46	26	9.34	6,850	0.10	1.25	Records good
White Clay Creek	Near Newark	87.8	32	110	9,080	4.7	1.25	Same
White Clay Creek	Above Newark	66.7	17	76.7	10,200	4.6	1.15	Same
Red Clay Creek	Near Wooddale	47.0	29	61.7	4,780	4.5	1.31	Same
Little Mill Creek	Elsmere	6.7	9	9.59	3,960	0.10	1.43	Same
Brandywine Creek	Chadds Ford, PA	287	52	381	23,800	42	1.33	Same
Brandywine Creek	Wilmington	314	26	451	29,000	56	1.44	Same
Coastal Plains Streams								
Christina River	Cooches Bridge	20.5	29	25.8	3,320	0.20	1.26	Records good
Blackbird Creek	Blackbird	3.85	16	4.47	712	0	1.16	Records fair

1/ As of 1972

2/ (CFS) Cubic feet per second. One CFS equals 646,323 gallons a day.

SUMMARY AND CONCLUSIONS

The Midvale-Llangollen Estates area as defined in this report consists only of two square miles. In the area the average daily pumpage in 1972 reached an estimated average of 6,700,000 gallons a day with peak summer and dry weather demands going as high as 9,000,000 gallons a day. The water used in 1972 came from three sources, namely: (1) the Lower Potomac artesian aquifer, (2) the Upper Potomac artesian aquifer, and (3) the Pleistocene and subcropping Upper Potomac water-table aquifer.

The ground-water reservoirs of the Potomac formation consist of sands in two general hydrologic zones in the Potomac formation. The Potomac is a formation in which clays are more dominant than sands. In the outcrop and subcrops of the two aquifer zones, the sands of the Potomac are mantled in places by sands of the Pleistocene so that, in places, sands of the Potomac and Pleistocene form a single water-table aquifer. These three aquifers supply all of the ground water pumped in the Midvale-Llangollen Estates area.

Wells in the Lower Potomac aquifer have been developed only at the Amoco Polymer Plant well field and at the Amoco Film Plant well field. The wells at the film plant are dually completed in both the Upper and Lower Potomac aquifers and for this reason little is known about either aquifer at the film plant. The deep aquifer in the Lower Potomac at the polymer plant has poor water-yielding properties. An extensive study and pumping tests by Leggette, Brashears and Graham made in 1961 reveal that the well will produce 400 gallons a minute (576,000 gallons a day) continuously and could produce up to 500 gallons for several weeks if the need should arise. The consultants also conclude

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that because of the very poor transmissive properties of the aquifer as demonstrated by the pumping test, the 250-acre tract in which the well is located will only support the one well. The Lower Potomac aquifer was also examined in a test well drilled on the Reni property just south of the Llangollen landfill. No promising source of water was found in the test well to a depth of 545 feet below land surface. Very little, if any, additional water can be assured by drilling more wells to the Lower Potomac aquifer in the Midvale-Llangollen Estates area. The Lower Potomac aquifer is not threatened, nor is it likely to be threatened, with contamination by leachate discharge from the Llangollen landfill because of the thick protective clay between the Upper and Lower Potomac aquifer zones.

Wells in the Upper Potomac artesian aquifer pumped an average estimated at 5,600,000 gallons a day in the two square mile Midvale-Llangollen Estates area in 1972. The Amoco Chemical Company has established use from the aquifer of about 2,000,000 gallons a day. Artesian Water Company used an average of 3,500,000 gallons a day in 1972. New Castle County has recently put into operation several wells for the purpose of retrieving leachate contaminated water in the aquifer from the Llangollen landfill. The County retrieval wells are designed to remove 3,000,000 to 4,000,000 gallons a day. Sand and gravel companies and others are using an estimated 100,000 gallons daily from the artesian part of the aquifer.

The limit of development of the Upper Potomac aquifer in the Midvale-Llangollen Estates area based on the rate of decline in artesian pressure caused by pumping the wells, the available drawdown to the top of the confining clay and the top of the screens, the estimated available recharge area and the transmissive and storage properties of the aquifer, appears to be not more than

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an average of about 6,500,000 gallons a day and may prove to be less. The developed capacities of wells to the Upper Potomac artesian aquifer in the Midvale-Llangollen Estates area by Amoco, Artesian Water Company, New Castle County and others far exceed the capacity of the aquifer to deliver water under artesian conditions on a long term basis. During the period of pumping to remove the water contaminated by leachate, it appears that a part of the normal pumping from the Upper Potomac aquifer in the Midvale-Llangollen area must be curtailed to bring the overall average of pumpage from the artesian aquifer to 6,500,000 gallons a day or less and to allow the necessary retrieval well pumpage. The Upper Potomac aquifer has received some landfill leachate contamination in about one fourth of the Midvale-Llangollen area. Retrieval of the contaminated water in the aquifer has been in progress by the Department of Public Works, New Castle County since November 1973. As of January 1, 1974, the contaminated area covered about 310 acres including the landfill area. In this area contamination occurs in places in the Upper Potomac aquifer, in the Pleistocene aquifer in the vicinity south of the landfill and in places along Army Creek and in Army Creek.

The development of ground water from the Pleistocene water-table aquifer has not been large in the Midvale-Llangollen Estates area because the saturated thickness of the Pleistocene is not sufficient to provide adequate drawdown in the aquifer to sustain the pumpage from large capacity wells. In the northern and northwestern part of the area where the Pleistocene is in direct contact with the subcrop of the Upper Potomac aquifer, wells of more than 300 gallons a minute have been developed under water-table conditions. Drillers' logs and water-level data indicate, however, that most if not all of the water is being obtained from the subcropping Upper Potomac aquifer.

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The Pleistocene water-table aquifer has much importance in collecting precipitation for recharge to the Upper Potomac aquifer supplying the area and in providing fair weather discharge to Army Creek and to the wetlands of the Delaware estuary.

The surface water resources of Army Creek in the Midvale-Llangollen Estates area are small in available quantity for water supply. The drainage area of the main stem of Army Creek above the marshlands and above its crossing by U. S. Highway 13 is about four square miles. The flow from the four square miles of drainage area is estimated to be equal to an average of five and twelve hundredths cubic feet per second or 3,300,000 gallons a day. Based on the records of Shellpot Creek, Little Mill Creek and Blackbird Creek, the minimum daily discharge of Army Creek during periods of prolonged drought is probably close to zero. Storage would be required to use Army Creek water exclusively for water supply.

Army Creek is important to the Midvale-Llangollen Estates area in providing fresh water drainage to the estuary and wetlands of the Delaware River.

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RECOMMENDATIONS

The foregoing report clearly shows that the Llangollen landfill is contributing leachate contaminants to the water-table aquifer, to the Upper Potomac aquifer, and to the flow of Army Creek in the vicinity of the Llangollen landfill. As of January 1, 1974, the report estimates that the affected area amounted to about 310 acres. New Castle County has already put into operation an extensive retrieval well program to recover the contaminated water in the affected area. The retrieval of the contaminated water is being withdrawn from the ground-water reservoirs at rates of 3,000,000 to 4,000,000 gallons a day, and the pumping must continue for more than two years to freshen the two aquifers. It is recommended that operation of the retrieval wells be continued until the contaminants are removed. In order to keep the aquifers and Army Creek fresh from contaminants after the retrieval program is completed, the only assurance of keeping the aquifers fresh at the Llangollen landfill is by removing the landfill, or by completely containing the leachate in the landfill, or by continuous protective pumping of the leachate drainage for many years to come. The protective pumping will waste much water that might be used for useful purposes and will be costly in operation and maintenance.

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